The challenge of implementing green gas into the gas supply

Jan Bekkering

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The challenge of implementing green gas into the gas supply

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VOORWOORD

De Prediker zei het al: Er is niets nieuws onder de zon. Vergisting van organisch materiaal is een proces dat al lange tijd toegepast wordt om gas te produceren welke bijvoorbeeld gebruikt kan worden om te koken. In landen als India en China wordt dit ook nu nog steeds gedaan. Daarbij wordt dan gebruik gemaakt van (deels) ondergrondse tanks vlakbij de huizen. In deze tanks worden uitwerpselen en groenafval vergist. Het digestaat kan als organische meststof nuttig worden gebruikt. Een ultieme vorm van decentrale energieproductie en denken in kringlopen.

Om verschillende redenen staat duurzame, decentrale energieproductie ook in het westen de laatste jaren weer volop in de belangstelling. Dit uit zich in nieuw onderzoek, nieuwe producten en nieuwe markten. Mijn promotieonderzoek maakt daar deel van uit, en handelt over ‘boerderijschaal’ groengasketens waarbij biogas uit mest en cosubstraat wordt opgewerkt tot aardgaskwaliteit en vervolgens geïnjecteerd in het bestaande aardgasnet. Dit onderzoek heeft tot het voorliggend proefschrift geleid.

Mijn promotieonderzoek heeft grotendeels plaatsgevonden binnen het gesubsidieerde project Flexigas, dat door RenQi is gefaciliteerd. In het project hebben diverse partners, elk met hun specialisme binnen de biogasketen, samengewerkt. Zonder deze facilitering, samenwerking en inbreng van andere partners binnen het project had ik dit proefschrift niet in de huidige vorm kunnen schrijven.

Ik waag me niet aan het uitputtend benoemen van alle mensen, binnen of buiten het projectverband, van wie ik steun heb ontvangen. De kans is te groot dat ik mensen vergeet en daarmee tekort doe. In elk geval wil ik mijn waardering en dank uitspreken voor alle collega’s en medewerkers binnen Flexigas, het kenniscentrum Energie en de opleiding Werktuigbouwkunde van de Hanzehogeschool die me gesteund hebben op welke manier dan ook: inhoudelijk, het faciliteren van de promotie, of door interesse te tonen. Een paar mensen in het bijzonder wil ik hier wel noemen: Mijn promotor Ton Broekhuis, copromotor Wim van Gemert en Evert Jan Hengeveld. Ton, bedankt voor de begeleiding. Je gevoel voor wat er wel toe doet en wat niet, en op het juiste moment op het juiste niveau aangeven wat er moet gebeuren; dat zou ik ook wel willen kunnen. Wim, ik herinner me dat we elkaar een aantal jaren geleden in de gang tegen kwamen en dat je zei: we moeten even met elkaar praten. Eigenlijk is dit proefschrift een uitvloeisel van die opmerking. Je blik op de horizon hielp om mijn onderzoek binnen het grotere geheel te blijven zien. Evert Jan, op jou kon ik bogen voor een accurate beoordeling van mijn

schrijfsels, de fysicus in jou kwam regelmatig naar boven bij je hulp en controle bij mijn berekeningen.

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Last but not least wil ik mijn vrouw Ans noemen: Bedankt dat je mijn promotieonderzoek vanaf het begin gesteund hebt! Ik heb al die tijd het idee gehad dat je het zag zitten en geloofde in de goede afloop.

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NOMENCLATURE

ABS	agent based simulation
CHP	combined heat and power
CSTR	continuously stirred tank reactor
DM	dry matter: the share (%) of biomass not being water
DSO	distribution system operator
End user	household or company that demands gas
FPE	fossil primary energy
FPEIO	fossil primary energy input – output ratio
GDC	gas demand coverage, i.e. the percentage of a concrete natural gas demand pattern replaced by green gas
GHG	greenhouse gas
GIS	geographical information system
GP	goal programming
Green gas	biogas upgraded to natural gas quality, in literature also referred to as biomethane
GRS	gas receiving station, where gas from the transport grid enters the distribution grid, and the pressure of the gas is reduced from 40 bar to 8 bar
HHV	higher heating value/(MJ/Nm^3)
IEA	International Energy Agency
LP	linear programming
MILP	mixed integer linear programming
Nm^3	normal cubic meter (at standardized conditions p = 1.01325 bar, T = 273.15 K)
oDM	organic dry matter: the share (%) of dry matter which consists of organic material
PE	primary energy
PEIO	primary energy input – output ratio
Primary Energy	energy as found in nature before having undergone any conversion
SNG	synthetic natural gas, consists of mainly CH_4, produced by gasification of coal or biomass followed by methanization

SSF	seasonal swing factor (-), defined by the maximum hourly gas demand divided by the minimum hourly gas demand in a year. SSF = 1 means a constant gas demand
VS	volatile solids

1

INTRODUCTION

'Every journey begins with a single step'.

This famous quotation is often an encouragement for someone who wants to undertake something large. You will not reach your goal if you do not start. In my opinion it also applies to renewable energy. Nowadays, at the time of composing this thesis, many people are involved in developments in renewable energy, in the world and also in The Netherlands. These developments can be considered to be a journey to replace fossil energy more and more. Much debate is going on which steps have to be taken. The Dutch energy covenant is an example of an effort to take such steps [1]. On a European level the Energy Roadmap 2050 gives direction [2]. The reason for taking steps is usually considered to be threefold:

1. Scarcity of energy. Scenario analyses show that global energy demand will grow to 2035, see Figure 1.1. Demand growth occurs mainly in emerging economies. China is important in this respect, but it will shift to India and, to a lesser extent, Southeast Asia. Energy from fossil resources will remain important the next decades.
2. Climate change. As the source of two-thirds of global greenhouse gas emissions, the energy sector will be pivotal in determining whether or not climate change goals are achieved.

3. Security of supply. The regions in the world where energy (oil, coal, natural gas) is available, are often not the regions where most energy is used (western Europe, the United States and Japan are clearly among them). High prices, but also possible political instability in supply regions, may cause supply problems.

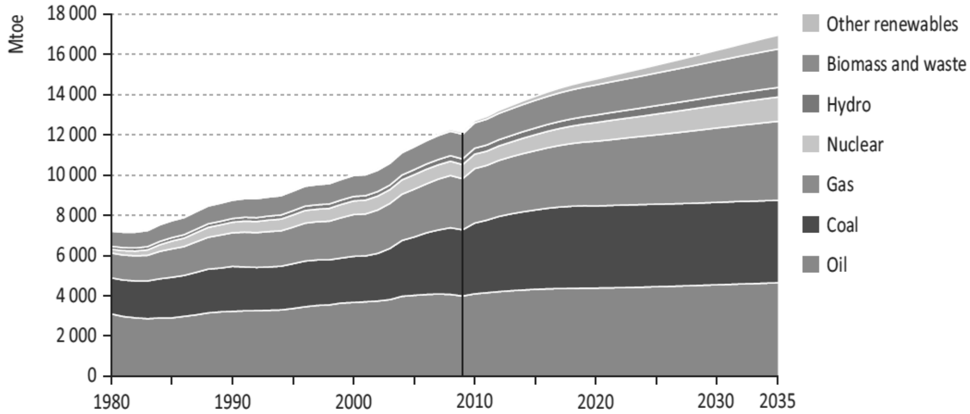

Figure 1.1: World primary energy demand by fuel ([3], new policies scenario).

To alleviate these problems, a range of renewable energy options can, and will, play a role, as depicted in the overview of Figure 1.2. It is generally believed that a variety of possibilities must be developed to reach renewable energy targets.

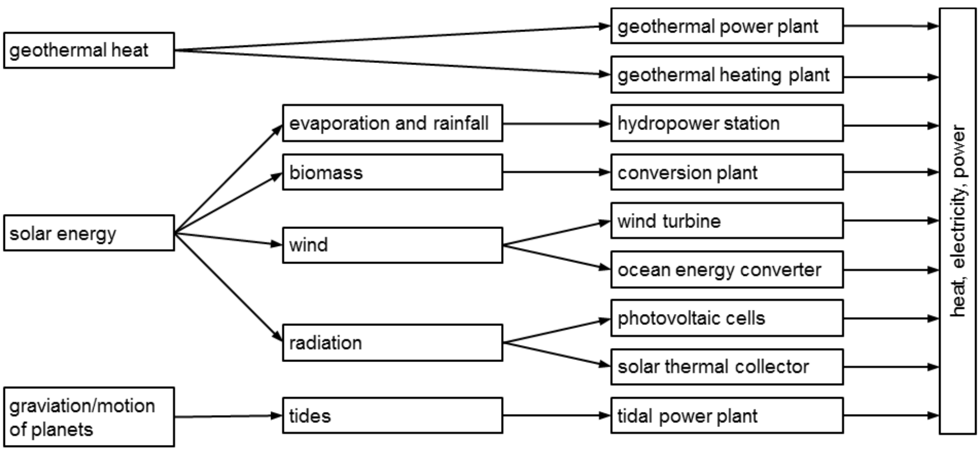

Figure 1.2: Overview of renewable energy resources and conversion routes to useful heat, electricity and power.

Biomass is one of the contributors. Compared to other resources, biomass is special. Except heat, electricity or power, materials can be produced as well from biomass. An overview of biomass utilization might look like Figure 1.3. A useful, systematic approach to using biomass might be cascading [4].

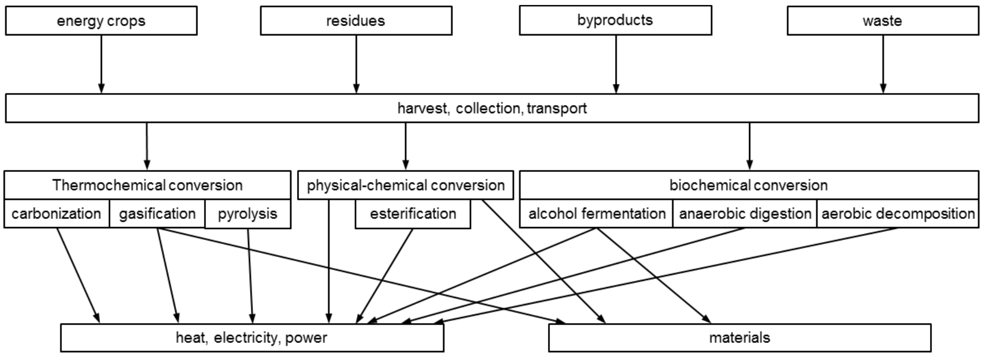

Figure 1.3: Biomass can be converted into energy or useful material.

Within this wide field of possibilities and potentially conflicting interests, it is difficult, if not impossible, to determine the optimal development and use of renewable energy sources and their applications, and biomass in particular.

In the Netherlands, natural gas currently delivers the largest share of the energy use (42 %), see Figure 1.4. 97 % of the Dutch households is connected to the natural gas grid. Oil has the second largest share with 38 %. The current share of renewable energy in the energy use is small (4 %).The Netherlands aims for 14 % renewable energy production in 2020 and 16 % in 2023 [1].

Looking into more detail at the natural gas grid, a transport grid and a distribution grid can be distinguished. In the current system, natural gas, from gas fields as well as imported, is transported through the high and medium pressure gas transport grid (>67 and 40 bar respectively). Generally, the transport grid is characterized by large pipe diameters, large flows and large transport distances. At gas receiving stations the gas enters the gas distribution grid, and the gas pressure is reduced to 8 bar. The distribution grid is further characterized by smaller pipe diameters, smaller flows and often a meshed grid. Residences and small industry are connected to the distribution grid, some large industry may be connected directly to the transport grid.

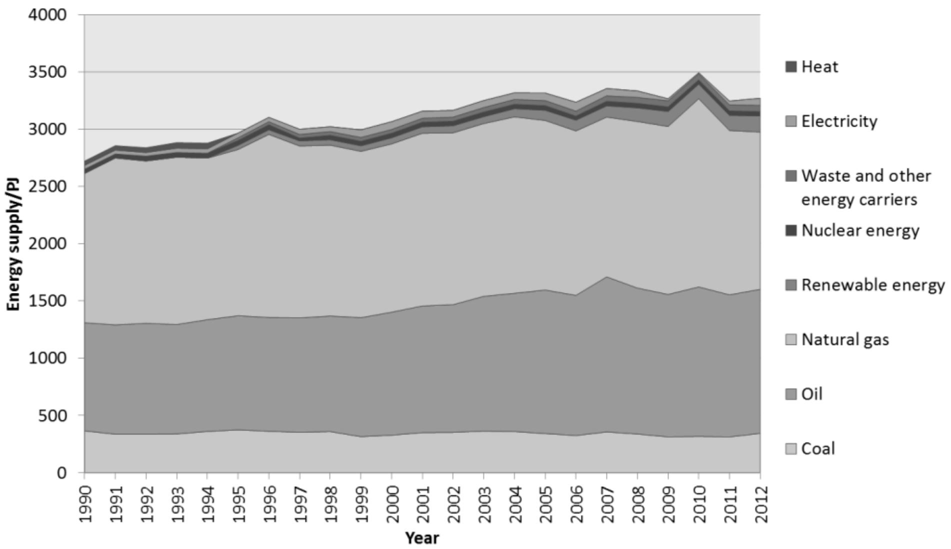

Figure 1.4: Energy use in The Netherlands, subdivided in energy carriers [5].

With the Dutch natural gas supply in mind, this thesis focuses on natural gas replacement by green gas from co-digestion, on a distribution grid level. Green gas is defined as gas produced from renewable sources and converted to natural gas standards, i.e., it has comparable properties to natural gas. As such they are interchangeable. The expression 'green gas' is typically used in the Netherlands, in other countries it is often referred to as biomethane. In this thesis the expression green gas is used.

The research field of green gas is broad, and comprises research into e.g. substrates, fermenter and upgrading technology, to potentials of biomass availability and the contribution of biogas to Dutch or European renewable energy initiatives. One of the white spots in current knowledge is the question how green gas supply systems might look like in practice. This is the scope of the study and is described in this thesis. In chapter two this is further explored and a direction for research is determined. This direction comprises paying attention to 'operational' aspects of green gas supply chains, with a focus on green gas from co-digestion of maize and cattle manure. As such, it can be read as an extension of this introduction. In chapter three this research direction is translated into the design of a model describing green gas supply chains. The resulting model aims to calculate the cost price of green gas as a function of scale, taking into account some practically determined sustainability aspects. The problem of balancing seasonal demand and supply is addressed by exploring regional variations in natural gas demand and comparing options for green gas supply chains. This is described in chapter four. The main conclusions of chapter four were used to propose an approach for designing a green gas supply for a rural region in The Netherlands, which is the topic of chapter five. Finally, in chapter six, some potential improvements of a green gas supply are further explored which might enhance a further implementation of green gas into the energy supply. As such, this thesis is about a journey into the possibilities of green gas. But it can be considered to be a first step as well, on a journey towards a more mature implementation of green gas into the Dutch gas supply. And further, on a journey where green gas finds its place among a range of renewable energy options.

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2

OPTIMIZATION OF A GREEN GAS SUPPLY CHAIN – A REVIEW

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Abstract
In this review the knowledge status of and future research options on a green gas supply based on biogas production by co-digestion is explored. Applications and developments of the (bio)gas supply in The Netherlands have been considered, whereafter literature research has been done into the several stages from production of dairy cattle manure and biomass to green gas injection into the gas grid. An overview of a green gas supply chain has not been made before. In this study it is concluded that on installation level (micro-level) much practical knowledge is available and on macro-level knowledge about availability of biomass. But on meso-level (operations level of a green gas supply) very little research has been done until now. Future research should include the modeling of a green gas supply chain on an operations level, i.e. questions must be answered as where

to build digesters based on availability of biomass. Such a model should also advise on technology of upgrading depending on scale factors. Future research might also give insight in the usability of mixing (partly upgraded) biogas with natural gas. The preconditions for mixing would depend on composition of the gas, the ratio of gases to be mixed and the requirements on the mixture.

2.1 INTRODUCTION

Ambitions of the Dutch government

Currently the share of natural gas, 45-50 billion m^3 [1], in primary energy demand in the Netherlands is about 42 %, including 14 million m^3 of green gas [2]. Production of heat (40 % of the Dutch energy usage) is almost totally depending on natural gas. In The Netherlands the gas use has been stable the last two decades, residential use has decreased slightly the last decade because of isolation and high efficiency burners. The IEA forecasts that till 2030 the gas demand will increase with 2 % a year (World Energy Outlook 2005). However, this is a decrease of the growth when compared to the period 1980-2004 (2.6 %).

The current share of sustainable energy in The Netherlands is less than 3 % (status 2006), and less than 2 % of this sustainable energy is (bio)gas [3]. The Dutch government aims for a share of 20 % sustainable energy and 30 % less greenhouse gases in 2020 (compared to the level in 1990, [4]). Concerning the gas supply chain, the future expectation is that almost 10 % of the natural gas can be replaced by green gas [2]. Although this does not meet the above mentioned goal of 20 % when considering the gas supply system separately, green gas will have an important influence on reaching these goals. On the other hand, published ambitions envision a share of 8-12 % of green gas in 2020, 15-20 % green gas in 2030 and 50 % in 2050 [5]. These higher percentages include gasification of biomass (SNG) and hydrogen.

The energy market in The Netherlands seems to move from supply driven to demand driven, at least in part. Customers are becoming more aware how energy is produced and many are willing to pay for ‘green’ energy. This raises questions about what sustainability comprises. Energy is produced more and more decentrally. In fact, we are talking about a transition instead of optimization or innovation [6].

The above considerations, in addition to matters of decreasing availability of fossil fuels and security of supply, justify research into the dynamics of the gas market. In order to understand the aforementioned transition and to investigate what is necessary for a transition, it is wise to investigate the total gas supply chain from producers of gas, transport, distribution to demand side (end users of gas).

Till now biogas is mainly converted to electricity. For small quantities this seems the most practical way of conversion, and till recently this was the only conversion of biogas which was subsidized by the Dutch government. However, basically there are four routes to transform biogas to useful energy:

1. Production of electricity
2. Production of heat
3. Production of heat and electricity
4. Upgrading to green gas and injection into the gas grid

A way of comparing these transformations is to calculate the savings of natural gas of every transformation. The sequence of these transformations when rated to decreasing energy efficiency, in terms of saving natural gas, is given below (with a rough indication of natural gas savings, see also [2]). It is convenient to compare the transformations of biogas in terms of energy (MJ) instead of m^3 because the heating value of biogas differs from that of natural gas.

1. Production of electricity and heat in a combined heat and power (CHP) installation: 1 MJ of biogas gives 0.50 MJ_{th} thermal energy and 0.38 MJ_e electric energy. The efficiencies are average values from practice. If biogas (and thus a CHP) is not available, the heat would normally have been produced in a local heater (boiler) with an efficiency η_{th}=0.90 and the electricity in a power plant with an efficiency η_e=0.55 (Combined Cycle). Losses for transport of electricity are not included. This means that for 0.50 MJ_{th} and 0.38 MJ_e 1.24 MJ of natural gas would be needed. So, 1 MJ of biogas would save 1.24 MJ of natural gas. Or, assuming a methane content in biogas of 65 %, 1.23 m^3 biogas would save 1 m^3 natural gas.
2. Heat production: burning 1 MJ of biogas in a heater would give 0.90 MJ_{th}, assumed that this is possible without problems. 1 MJ of natural gas would give the same result. Thus, again with a methane content of 65 % in biogas, 1.54 m^3 biogas would replace 1 m^3 natural gas.
3. Upgrading to green gas and injection into the gas grid: 1 MJ of biogas would give 0.75-0.91 MJ of green gas. The value depends on the way of upgrading. Upgrading not only requires energy for the process itself, but also differences exist to what extent the process is able to separate the methane from other components (methane losses).

Anyway, 1 MJ of biogas would save 0.75-0.91 MJ natural gas. Or, 1.69-2.05 m^3 biogas would replace 1 m^3 natural gas.

4. Production of electricity: this would be done in a gas engine. With an efficiency of η_e=0.38, 1 MJ of biogas would produce 0.38 MJ of electric energy. Without biogas the needed electricity would be produced in a power plant. With an efficiency of η_e=0.55 (Combined Cycle) 0.69 MJ natural gas would be needed to produce 0.38 MJ (without taking transport losses into account). Or, 2.23 m^3 biogas would replace 1 m^3 natural gas.

Some remarks can be made about the above comparison. Although CHP and heat production seem the most efficient, the problem is that the heat is often not needed at the location where the biogas is available. This is why these two options are not applied often. Especially for the first option, the question arises why not using a CHP running on natural gas when both heat and electricity are needed, instead of electricity from the grid and heat from a boiler. Then only 1 MJ natural gas would be necessary instead of 1.24 MJ. Of course, the above consideration is only one way of looking at applications of biogas. Another route would e.g. be to investigate to which rate the distinguished applications would meet sustainability criteria, which would include energy efficiencies of producing biogas or natural gas. In practice, there might be quite different reasons to choose a transformation of (bio)gas. Nevertheless, it seems justified to do research in upgrading biogas to green gas and injecting it into the gas grid. At least it can be said that, from an efficiency point of view, upgrading to green gas and injecting in the grid is much better than producing electricity which is currently, in most cases, common practice. For using biogas as a vehicle fuel the green gas route should be followed as well [7]. Also for usage in a fuel cell gas treatment is necessary.

Roughly, the Dutch potential of 10 % green gas consists of 1500 million m^3 green gas from digestion and 3500 million m^3 green gas from gasification [2]. Gasification is most promising in large-scale centralized plants. In this paper the focus will be on decentralized gas production. In the current situation (2008) 13 million m^3 green gas per annum is produced in four landfill sites and one sewage gas installation. Because waste flows will not significantly increase, it seems reasonable that the green gas production from landfill sites will not exceed 15 million m^3, and that the maximum of green gas from sewage gas is 4-5 million m^3. Based on available material which can be digested, co-digestion has a green gas potential of 1500 million m^3 per annum [5]. So, among the possibilities of digestion, co-digestion has the most significant share. A minor share (±25 %) of this co-digestion consists of swill and other waste products [8]. The major share can be produced by digesting manure and agricultural crops. Therefore, it is interesting to investigate the green gas supply chain based on co-digestion of manure and agricultural crops. Figure 2.1 shows how such a supply chain looks like: Manure and co-substrates are digested, and the biogas is upgraded to natural gas standards and injected into the gas grid.

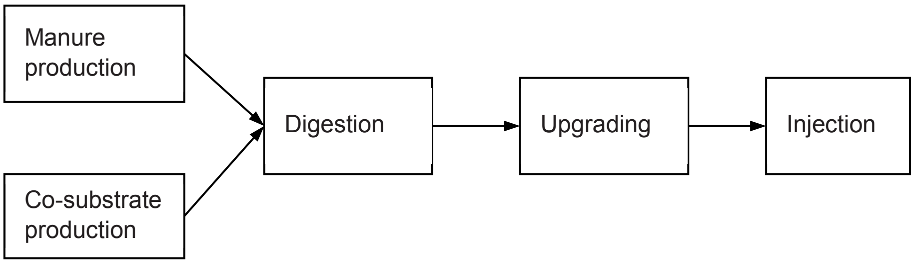

Figure 2.1: The chain approach of a green gas supply. The main processes in the chain are shown. Between every block transport and storage can be thought.

All activities in producing green gas can be done on one (centralized) or more (decentralized) locations. Many choices can be made, every choice having its transport and storage costs, and a scale of economy can be calculated. In order to get insight in the complexity of such a supply, literature research on the supply chain of Figure 2.1 has been done, which is described in the following section. Because of our interest in operational matters of a green gas supply, special focus will be on costs, scale of economy and stability of the processes. After this literature overview, the literature will be discussed and in the final section conclusions are drawn together with a view on future research.

2.2 OVERVIEW LITERATURE

Many research programmes on digester gas investigate technologies which are related directly to one of the blocks in the chain of Figure 2.1.

2.2.1 Manure and co-substrates

Availability of manure and biomass are generally described on a macro-level. Production of manure in the Netherlands was investigated [9]. Koppejan and De Boer-Meulman [8] investigated the availability of biomass in the Netherlands and abroad (the latter should be imported) in order to meet the need in 2010, and in relation to costs and subsidies. The need is based on all applications of biomass concerning heat and electricity. One of the conclusions is that import is needed to meet the targets, but also that the economy of biomass conversion strongly depends on the prices.

2.2.2 Digesters

General information about digesters and their role in sustainable energy production is available in several books and documents (see e.g. [10], [11], [12], [13]). Two approaches seem to be common nowadays to get insight in digestion processes: the experimental approach in which the influence of parameters on digestion are measured, and a more theoretical approach in which digestion processes are modeled in a mathematical way. The latter calculates the biogas production from a given input analyzing the chemical structures. Both approaches are presented below. Ward et al. [14] investigated the state-of-the-art of anaerobic digestion of agricultural resources by literature. The main focus in this research was on the experimental knowledge. An overview of important parameters influencing not only the anaerobic digestion process but also the costs (qualitatively) is listed in Table 2.1.

Parameter	**Influence on biogas production and costs**
Reactor design	Generally three types of reactors can be distinguished: one-stage batch reactors, one-stage continuously fed systems, and two-stage (or multi-stage) reactors in which the hydrolysis/acidification and acetogenesis/methanogenesis are separated. Multi-stage systems seem to be more stable than single-stage systems. Instability can be caused by fluctuations in organic loading rate, heterogeneity of wastes or excessive inhibitors. Multi-stage systems provide some protection against a variable organic loading rate as the more sensitive methanogens are buffered by the first stage (see e.g. [15], [16]). However, multi-stage digesters are more expensive to build and maintain, but are generally found to have a higher performance than single-stage digesters.
Mixing	Mixing is done to ensure efficient transfer of organic material for the active microbial biomass, to release gas bubbles in the medium and to prevent sedimentation of denser particulate material. The effect of mixing depends on the type of substrate. In laboratory-scale research it was found that production of biogas was equal for mixed and unmixed digesters when fed with 5 % cow manure slurry. With 10 % or 15 % slurry mixing proved to be effective. Moreover, mixing during start-up was not beneficial [17]. Also the way of mixing (continuous or intermittent in various intensities) influences the methane production depending on the type of substrate [18].
Temperature	Digestion can take place at psychrophilic, mesophilic or thermophilic temperatures. Mesophilic and thermophilic are most commonly applied. Which of these two is the most efficient is difficult to say, there is some evidence that the total methane yield is somewhat higher in a mesophilic process, but that the retention time is shorter in a thermophilic process [19]. The heat needed for maintaining the temperature is normally delivered by a gas motor which is used for producing electricity from biogas. In case of upgrading the biogas, instead of producing electricity, the

	costs for producing heat might be high. Chae et al. [20] investigated the mesophilic anaerobic digestion of swine manure and showed that methane yield increased with increasing temperature. However, this does not mean the higher the temperature the more optimal, due to the larger energy requirement at higher digesting temperatures. Therefore, careful consideration of the net energy balance between the increased heating energy demands and improved additional methane production at higher operating temperatures must be simultaneously taken into account when deciding the economical digesting temperature.
Type of substrate	Co-digestion of manure and biomass increase the methane yield when compared to digesting solely manure (see e.g. [21]), but the results are sensitive to many operating parameters: not only the reactor parameters as discussed before but also the type of manure and biomass and ripeness of biomass ([22], [23]). Costs highly depend on the type of biomass, energy maize is expensive, while grass as a waste product may have a negative price.
Pretreatment	Pretreatment of biomass is especially useful when these have a high cellulose or lignin content. Pretreatment can be done chemically, thermally or physically. Thermal pretreatment generally takes place at 80°-140°. Mechanically decreasing the particle size of biomass increases the methane yield [24]. In both cases the consequences for the costs are evident.

Table 2.1: Parameters influencing (the costs of) anaerobic digestion processes.

The other type of published research is by modeling. Gerber and Span [25] reviewed and discussed several mathematical models for anaerobic digestion. The existing models vary with respect to their objectives and complexity. Comparatively simple models have been developed to calculate the maximum biogas rate, which theoretically can be produced from organic structures. On the other hand, research has been done in mathematical modeling of anaerobic digestion processes in general, with the aim to develop a generally applicable model. One of these investigations resulted in the Anaerobic Digestion Model No. 1 (ADM1; [26]). ADM1 is a structured model with disintegration and hydrolysis, acidogenesis, acetogenesis and methanogenesis steps. This model has been applied and modified by Lübken et al. [27] to simulate energy production of the digestion of cattle manure and renewable energy crops. In this research an energy balance was added, which enabled the calculation of the net energy production. In this energy balance the electrical energy production, mechanical power of the pump and stirrer, thermal energy production, radiation loss and heat requirement for substrate heating were taken into account. It was found that calculations of different kinds of energy losses for a pilot-scale digester showed high dynamic variations. Blumensaat and Keller [28] used a modified ADM1 to model a two-stage anaerobic digestion. The results of the model were compared to data from experimental pilot-scale experiments with good agreement.

Whatever method is taken, the aim for highest efficiency at the lowest costs is evident. The costs of biogas and electricity production from maize silage in relation to plant size were investigated by Walla and Schneeberger [29]. In this research a model was developed to derive cost curves for the unit costs of biogas and electricity production and for the transport costs for maize silage and biogas slurry. It was found that the least-cost plant capacity depends to a great extent on the local availability of silage maize.

2.2.3 Upgrading biogas to natural gas quality

Upgrading of biogas is necessary in order to meet requirements which are demanded not only by the application of the gas (burners), but also by the gas grid which transports the gas. In general green gas specifications should meet the local or national requirements. In Table 2.2 typical values of biogas from co-digestion are compared to the Dutch requirements for gas in the distribution gas grid.

Quality component	Unit	Biogas from co-digestion (typical values)	Requirement from Dutch Authority of Competition– regional grid – boundary values [30]
CH_4	vol%	63 (variation 53-70)[a] 45-75[b]	-
Higher hydrocarbons	vol%	0[a]	-
CO_2	vol%	47 (variation 30-47)[a] 25-55[b]	-
Nitrogen	vol%	0.2 (variation 0)[a] 0.01-5.00[b]	-
Upper heating value	MJ/Nm^3	-	31.6 – 38.7
Lower heating value		23[a]	-
Higher Wobbe-index	MJ/Nm^3	27[a]	43.46 – 44.41
Water vapour	vol%	1-5[b]	-
Water dewpoint	°C	35[b]	-10 (8 bar)
Temperature (of injected gas)	°C	-	0 – 20
Sulphur (total)	mg/Nm^3	-	45
Anorganic sulphur (H_2S)	mg/Nm^3	<1000 ppm (variation 0-10000)[a] 10-30.000[b]	5
Mercaptanes	mg/Nm^3	-	10

Odor	mg/Nm^3	-	>10, nom 18 – 40
Ammonia	mg/Nm^3	<100 ppm[a] 0.01-2.50[b]	3
Chlorine containing compounds	mg/Nm^3	0-5[a]	50
Fluor containing compounds	mg/Nm^3	-	25
Hydrogenchloride (HCl)	ppm	-	1
Hydrogencyanide (HCN)	ppm	-	10
Carbonmonoxide (CO)	mol%	<0.2 vol%[b]	1
Carbondioxide in dry gas grids (CO_2)	mol%	-	6
BTX (benzene, toluene, xylene)	ppm	0[b]	500
Aromatic hydrocarbons	mol%	-	1
Oxygen in dry gas grids	mol%	0[a] 0.01-2.00[b]	0,5 (3)
Hydrogen	vol%	0[a] 0.5[b]	12
Methane number	-	>135[a] 124-150[b]	>80
Dust	-	-	technically free
Siloxanes	mg/Nm^3	traces[b]	5 ppm

Table 2.2: Properties of biogas from co-digestion and requirements for gas in the gas grid. The data for biogas are taken from: [a][7], [b][10].

Concerning the requirements in relation to infrastructure, it is known that sulphur and hydrogen influence the integrity of pipelines. But very little literature can be found about gas mixtures or the influence of variations of gas specifications in relation to requirements. However, in order to understand the consequences of injecting other gases into the gas grid than natural gas, much can be learned from recent research in hydrogen [31]. The effect of hydrogen addition on thermodynamic and transportation properties of the mixture is investigated by Schouten et al. [32]. In this study it was shown that injection of 25 % hydrogen may lead to a temperature drop of several degrees, the temperature drop at the pressure reduction stations reduces by 1/3, and the pressure drop in the transport lines increases only slightly. The influence of hydrogen on combustion properties has been investigated. Coppens et al. [33] found that in lean flames enrichment by hydrogen has little effect on NO, while in rich flames the concentration of nitric oxide decreases significantly. Changes in the combustion behavior of methane upon hydrogen addition were investigated by characterizing the autoignition behavior of methane/hydrogen mixtures in a rapid compression machine [34]. The experimental results obtained under stochiometric conditions showed that replacing methane by hydrogen reduced the measured ignition delay time.

Concern exists about pathogens in biogas. Some research has been done into this field [35]. Possible options to reduce the risk of pathogens include heat treatment of the substrate, longer retention times in the digester and filtration. On the other hand questions must be answered concerning the risks and effects of production steps (e.g. upgrading) on pathogens. Vinneras et al. [36] sampled condensate water from gas pipes and gas from different parts of biogas upgrading systems. They found that the number of microorganisms found in the biogas corresponds to the original population in natural gas and concluded that the risk of spreading disease via biogas is very low since no pathogens were identified. Practice shows that green gas from landfill sites has been injected in the Dutch gas grid for years without known problems.

So, although much can be said yet about correct requirements, the requirements as listed in Table 2.2 are generally taken as a starting point to consider upgrading techniques for biogas. The steps taken for upgrading biogas to green gas (natural gas quality) are usually gas drying, gas desulphurization (removing H_2S), methane enrichment (removing CO_2) and removing other parts (e.g. siloxanes) if necessary. Currently used techniques for upgrading biogas are water scrubbing, pressure swing adsorption (PSA), membrane or cryogenic separation. An overview of these techniques is given by e.g. [7], [37] and [38]. A more extensive evaluation of upgrading techniques including economic aspects can be found in [39] and [40]. The choice for an upgrading technique is in practice not only determined by investment and operations costs, but might also be affected by matters as availability of water or the market position of a supplier. Some general data on upgrading techniques are given in Table 2.3.

Upgrading method	Water scrubbing	Vacuum Pressure Swing Absorption (VPSA)	Membrane	LP Cooab (chemical absorption technique)
Energy need/Nm^3 cleaned gas:				
- Electricity (kWh_e)	0.4 (0.3-0.6)	0.25 (0.3-1.0)	0.14	0.12
- Heat (kWh_{th})	0	0	0	0.4
Methane efficiency	97 %	97 %	82 %	99.9 %
Total efficiency:				
- without heat recovery	91 %	93 %	80 %	92 %
- with heat recovery	91 %	93 %	96 %	98 %

Table 2.3: Comparison of upgrading techniques for a biogas case containing 65 % methane, and including compression to a 4 bar gas grid. Data are from [39] and [41].

Research into the water wash upgrading technique has been done by Rasi et al. [42]. The objective of this study was to determine the feasibility of a countercurrent absorption process with a new type of design with a small height-to-diameter ratio (3:1 instead of the more conventionally used 20:1). Absorption columns used in water absorption processes are typically 10 m in height to achieve maximum contact surface between the gas and water phase, and upgrading is done at 9-12 bar pressure. In this study higher pressure compensated for the lack of column height. With higher pressure, also less water is needed. An interesting method under development is in situ methane enrichment ([43], [44]) because the total cost for in situ methane enrichment digestion is estimated to be significantly lower than the costs for conventional post-digestion upgrading of biogas.

2.2.4 Injection

Injection of (green) gas into the gas grid normally exists of the following steps:

1. Gas pressure controlling;
2. Gas compression;
3. Gas measurement (flow);
4. Gas storage;
5. Odorizing (adding THT);
6. Gas mixing;
7. Gas analysis.

These steps are common practice and are rather straightforward. The costs highly depend on injection location, pressure and quantity.

2.2.5 The green gas supply chain

Except scientific knowledge on specific 'blocks' in the gas supply chain (Figure 2.1), knowledge on behavior of (parts of) the gas supply chain is important. Although not much information is available yet, information on parts of the chain can be found. In a research the energy efficiency in the production and transportation of different kinds of biomass in Sweden has been analyzed in the current and estimated future situation, as well as the change in energy efficiency resulting from a transition from fossil-fuel-based energy systems to biomass-based systems [45]. In this research the energy yields of different crops are investigated, as well as the energy inputs needed, such as motor fuels, and the indirect use of fuels employed in the production of, for example, seeds, pesticides and farming machinery. A table with energy use per km per GJ transported biomass is presented, as well as a table with the net energy yield (energy content of biomass – energy input) based on a fixed transport distance. In this study the energy input per unit biomass was lowest for straw, logging residues and Salix, equal to 4 to 5 % of the energy output. It was also found that a transition from a fossil-fuel based energy system to a CO_2-neutral biomass-based system around the year 2015 is estimated to increase the energy input in biomass production and transportation by about 30 to 45 %, resulting in a decreased net energy output of about 4 %. Berglund and Börjesson [46] describe the energy performance in the life-cycle of biogas production. The energy content of biogas is compared to the needed energy for growth and transport of biomass and operation of a biogas plant. The results showed that the energy input into biogas systems overall corresponds to 20 to 40 % of the energy content in the biogas produced. The net energy output turned negative when transport distances exceed approximately 200 km for manure. The results are substantially affected by the assumptions made about the properties of the biomass and systems. Also the bottlenecks (technical, legislation, economical) which have to be alleviated in order to preserve the gas market [5] have been investigated. Polman et al. [47] also give an interesting overview of these bottlenecks: the aspects technology, economy, safety, legal aspects and environment have been investigated for parts of the supply chain: injection, infrastructure, measurement, application. Bottlenecks exist mainly in the area where technology meets economy, and on law and legal aspects.

2.3 Discussion - challenges

Studies on availability of biomass in a country are valuable in the sense that an overview is achieved of the potential in a country to meet e.g. sustainability goals by using biomass for energy. This is generally known as macro-level knowledge. In this study the major share of the found literature concern techniques for producing or upgrading biogas. These studies are important because a sound understanding of technology is necessary to design cost-effective installations which are able to produce gas that meets the requirements. The knowledge gained in this way can be interpreted as knowledge on micro-level. From a systems design or systems engineering perspective, it is also important to be able to understand the relations between the technologies. At this level, the meso-level, modeling of a green gas supply chain could be done. In order to get a profound understanding of a green gas supply, knowledge on these three levels is necessary. This is illustrated for other systems by e.g. [6] and [48].

We believe that on meso-level still a knowledge gap exists, because little literature can be found thus far on this level. More detailed research would be necessary when insight in a local biomass supply to a digester is needed, which is also recognized by e.g. [29] and [49]. They investigated economic aspects of biogas plants producing electricity. The aforementioned study by Berglund and Börjesson [46] seems to be a good starting point to expand this field of investigation, because here a system from growing crops to producing biogas is already analyzed. But questions arise about how the knowledge on parts of the green gas supply chain can be combined in order to describe or optimize a green gas supply in a given situation in a specific geographical region. As an illustration: the above mentioned target of 1500 million m^3 green gas means that ~2500 million m^3 biogas has to be produced annually, assuming that roughly 60 % of biogas consists of methane. An average digester on a farm in The Netherlands has an output of ~300 m^3 biogas per hour [50]. Suppose in one year 8500 operating hours are possible. Then each year 2.55 million m^3 biogas is produced on one farm. In this case 2500/2.55 = 980 digesters would be needed in The Netherlands.

Besides questions concerning gas quality and gas production and upgrading technology, new questions arise, such as: are so many digesters desirable, how should these be connected to the grid, can an economy of scale be calculated? It seems logical that the local availability of manure and biomass determine the location of a digester and hence the type and output of a digester. It is evident that for smaller installations these problems would even be more challenging. Insight in the most economic way of digester locations and their capacities is necessary. This could be done by developing an operational model. State-of-the-art knowledge of technologies, which include efficiencies and costs, combined with operations research techniques should give opportunities to obtain insight in optimal locations and capacities of digesters and upgrading plants.

Taking the current discussion in The Netherlands on sustainability into consideration, developing good sustainability criteria seems to be essential for such a model. For the Dutch situation, a good starting point for sustainability criteria seems to be [51]. In this document the criteria are divided in six themes: (i) greenhouse gas balance, (ii) biomass should not compete with food, local energy supply, medicine or building materials, (iii) biodiversity, (iv) people, (v) planet, (vi) profit. Part of these criteria should be a sound energy balance for such a gas supply chain for which [45] and [46] could be taken as a reference. A mass balance would give insight in (waste) flows in relation to costs. Gerin et al. [52] consider the energy and CO_2 balance of maize and grass as energy crops for anaerobic digestion. Ecological aspects of biogas production from renewables is also explored by [53]. Legislation and environmental aspects should be taken into account. The tension between economic benefits and environmental and social aspects has also been explored by [54].
An operational model should give answers on questions like e.g. where to build digesters and to what extent can upgrading installations be built decentrally. With such a model the sensitivity to changes of parameters could be investigated. Finally, challenges for improvement can be investigated systematically, including their usefulness.

Sound requirements on green gas is still a field of research. Polman [38] states that further research is needed on the influence of bacterias, phosphines, burning behavior of halogenated hydrocarbons and the possibility of microbiological corrosion of piping. The requirements listed in Table 2.2 seem to be based on calorific values and known influences of some hazardous elements on piping and burner components. A specific mix of components of the green gas is not required. However, this mix strongly influences aspects like heating value, Wobbe-index, knock phenomena, flame lift, blow out, flashback, soot formation and emissions. Together with an operational model it might be interesting to investigate the possibilities to adapt requirements to region and application.

An interesting field of research might be that fully upgrading of biogas to natural gas is not necessary in many cases. Very little is known about the possibilities of mixing off-spec gas with natural gas off-line. The technical and economic aspects of this should be investigated. The extent to which biogas can be mixed with natural gas depends on the required quality of the mixture and on flows (available quantities) of biogas and natural gas. For the latter an important parameter is the daily and seasonal fluctuation of the demand.

2.4 CONCLUSIONS

The knowledge status of a green gas supply chain on biogas production by co-digestion is reviewed. Although the explored investigations into the several stages from production of manure and biomass to green gas injection into the gas grid are valuable and recommendations for improvement are done, an underpinned view on how such a sustainable gas market would look like on an operational level seems to be lacking. Questions arise about the amount and location of needed digesters, to what extent upgrading installations can be built decentrally, how these should be connected to the gas grid, and about the possibilities of calculating an economy of scale. An operational model, meeting further defined sustainability criteria, should give answers on these kind of questions. With such a model the sensitivity to changes of parameters should be investigated. Challenges for improvement can be investigated systematically, including their usefulness. An interesting outcome might be that fully upgrading of biogas to natural gas is not necessary in many cases. The possibilities of mixing off-spec gas with natural gas in terms of economics should be investigated. Preconditions for mixing would depend on composition of the gas, the ratio of gases to be mixed and the requirements on the mixture. Finally, the risk of pathogens and possible solutions must be investigated further.

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3

OPERATIONAL MODELING OF A SUSTAINABLE GAS SUPPLY CHAIN

This chapter is based on the following paper: Bekkering J, Broekhuis AA, Gemert WJT van. Operational modeling of a sustainable gas supply chain. *Eng. Life Sci.* 2010;10(6):585-594.

Abstract

Biogas production from co-digestion of cattle manure and biomass can have a significant contribution to a sustainable gas supply when this gas is upgraded to specifications prescribed for injection into the national gas grid and injected into this grid. In this study we analyzed such a gas supply chain in a Dutch situation. A model was developed with which the cost price per Nm^3 was presented as a function of scale (Nm^3/h). The hypothesis that transport costs increase with increasing scale was confirmed, although this is not the main factor influencing the cost price for the considered production scales. For farm-scale gas supply chains (approximately 150-250 Nm^3/h green gas) a significant improvement is expected from decreasing costs of digesters and upgrading installations, and efficiency improvement of digesters. In this study also practical sustainability criteria for such a supply chain were investigated. For this reason the digestate from the digester should be

used as a fertilizer. For larger scales the number of transport movements in the supply chain seems to become a limiting factor in respect to sustainability.

3.1 INTRODUCTION

Biogas production from co-digestion of cattle manure and biomass can have a significant contribution to a sustainable gas supply when this gas is upgraded to specifications prescribed for injection into the national gas grid and injected into this grid. In this study we define 'biogas' as being crude gas obtained by fermentation and 'green gas' as being gas which is upgraded to natural gas standards, so it could be used as a substitute for natural gas. In other literature this substitute gas is sometimes referred to as 'biomethane'. Basically with 'sustainable' we mean that the needs of the present generation can be met without compromising the ability of future generations to meet their own needs (Brundtland definition). Data on availability of biomass and manure are usually available at a macro-level when the potential of a certain region, often a country or even larger, for supplying biomass or generating renewable energy is investigated [1, 2]. However, meeting the ambitions of a future sustainable gas supply, also questions should be answered like: where to build digesters and upgrading installations, where to inject green gas into the gas grid, what is the impact of transport, and: what scale is optimal in this respect. These questions were reviewed before in [3] which showed that green gas injection into the gas grid is a good option for biogas usage from an energy efficiency point of view.

The operational problem sketched above was previously investigated in an Austrian setting [4]. In this study the costs of biogas and electricity production from maize silage in relation to plant size were investigated. The plant size was also related to the subsidy available and the graduated tariff for green electricity in Austria. No conclusions were drawn on the sustainability of such an energy supply chain. Neither was this the case in a study where four different scenarios for biogas production and application were analyzed economically [5].

It is often assumed that generating renewable energy is sustainable, and therefore often the focus is solely on economy when it comes to design of bioenergy systems. Aiming for large scales seems a logical consequence. The correctness of this may be questioned. At least sound criteria are required to judge sustainability. No general conclusions on the average environmental impact and energy performance of biogas production can be drawn without accurate specification of the biogas system considered. Biogas is not always the best alternative when compared to other bioenergy systems. E.g., if heat is demanded and the raw materials can be combusted, or the arable land can be used for the cultivation of willow, the introduction of biogas could increase the emission of greenhouse gases [6]. Another study also concluded that production and use of biogas might present risks for the environment [7]. In a study on bioenergy from grasslands it was concluded that no general assessment on biodiversity could be made, since impacts are site-specific and depend on the initial situation and the direction of change [8]. E.g., when converting intensive grassland use from forage for dairy farming to biogas feedstock, management intensity might decrease through reducing the mowing frequency. On the other hand, using extensive grassland for biogas feedstock production might conflict with biodiversity targets since attempting intensification would be the obvious target for a farmer.

Also the applicability, economic efficiency and sustainability of different techniques for energy production from grassland as well as from grassland converted into maize fields, or short rotation poplars under German conditions, was investigated [9]. One of the conclusions in this study was that a verdict about sustainability of an energy supply chain is determined by the significance which is given to different criteria, e.g. focusing on greenhouse gas reduction would lead to another application of land use than focusing on biodiversity.

In this paper, we deal with the Dutch situation. And instead of focusing on producing electricity, we focus on upgrading and injection of green gas. Therefore, the goal of this paper is to get a better understanding of what a typical (small scale) sustainable gas supply chain, based on biogas production by co-digestion, would look like in The Netherlands. More specific, in our study the focus is primarily on the three northern provinces of The Netherlands (Friesland, Groningen, Drenthe), because of the above average agricultural activities in this region. The land area of these provinces is approximately 831 600 ha and the average agricultural area from 2005 till 2009 was 267 973 ha (approximately 32.5 % of the total land area).

The paper further addresses the following sub-questions:

i. What is the cost price of production and grid injection of one Nm^3 green gas based on co-digestion in relation to scale within chosen system boundaries?
ii. What sustainability criteria should be taken into account for such a supply chain, and what should these criteria be based on?
iii. How is sustainability related to scale?

The approach for answering these questions is outlined below.

3.2 METHOD AND ASSUMPTIONS

A calculation model was developed which enabled us to perform calculations on cost price and sustainability aspects of a green gas supply chain. Such a green gas supply chain based on co-digestion may be visualized as shown in Figure 3.1. The chain is represented by seven transformation blocks: biomass production (BM), transport (TR) and storage (ST) of biomass and manure, biogas production (DG), digestate handling (DS), biogas upgrading (UP) and green gas injection into the gas grid (IN). The system boundary is resembled by the frame around the blocks. For every block input and output streams are defined. The main stream is a physical stream, basically from left to right, from seed and cow manure to green gas. The arrows between the blocks represent the routing direction in the chain. Thus, for a given quantity of manure and produced biomass, the produced quantity of biogas and the injected amount of green gas can be calculated. Besides that, for every block the dotted arrows depict auxiliary streams which are not used further downwards in the stream. These auxiliary streams describe costs and sustainability items. With the totals of these auxiliary streams the cost price and sustainability criteria per Nm^3 injected green gas are calculated.

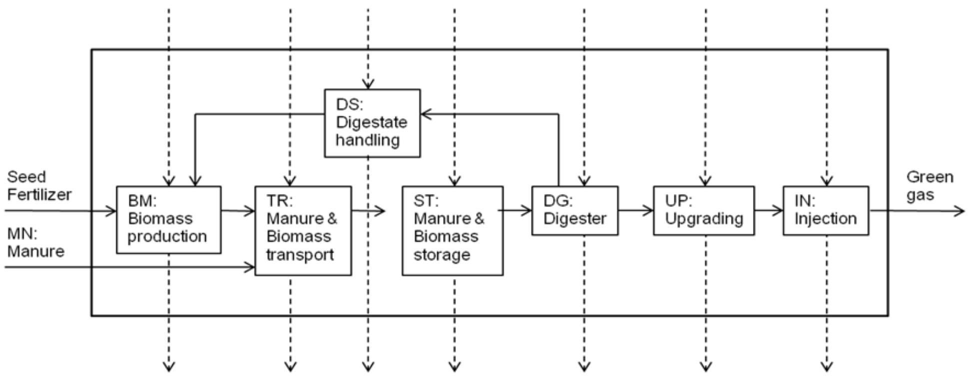

Figure 3.1: A green gas chain based on co-digestion is represented in seven transformation blocks.

3.2.1 Assumptions

An average farm in the north of The Netherlands comprises 85 cows and 65 ha land, based on statistics (Dutch Office for Statistics). These numbers determine the amount of manure and biomass production by this farm and are taken as a reference. If more biomass and manure are needed for a desired biogas production facility, these have to be bought from farmers in the surroundings. Further assumptions in our research, specifically related to the transformation blocks, are discussed below. Because of specific properties and assumptions on manure this input stream is also discussed. Data and references used in the model and belonging to the assumptions can be found in Table 3.1.

Manure (MN):

- Farmers with dairy cattle have a known quantity of manure each year. This has to be stored (shed periods), whether there is a digester or not. Common practice is that the costs for this storage, and environmental effects, are allocated to cattle farming and not to biogas production. For this reason manure is considered an input into the system.
- In the Netherlands more manure is produced than can be used as fertilizer. This means that farmers have to pay to get rid of manure, although prices vary from region to region. On one hand, this means that when a farmer digests the manure produced on his farm, part of it will be transformed into biogas, so the amount of manure left will be less. On the other hand, if a farmer digests the manure of other farmers, the latter will be willing to pay for this. This is resembled in our model by an average, but negative cost price for manure.

Biomass (BM):

- For a desired production of biogas the amount of needed biomass is taken equal to the amount of manure. According to Dutch legislation the obtained digestate can be classified as manure and can thus be used as fertilizer.
- The needed land area is assumed to be circular with the digester in the center point. This stresses that the activities are as local as possible. It is evident that making another assumption would influence cost price and sustainability negatively.
- Maize silage production is used as the reference case. E.g. [25] confirms that maize is often used for co-digestion because of its high biogas yield.
- Maize production covers 25 % of the farmer’s land. Although the number is more or less arbitrarily chosen, we assume that fallow lying land can be used for growing energy crops and part of the current crops can be replaced by energy crops. Dutch statistics show a percentage of less than 1 % of the arable land being fallow lying. Decreasing the 25 % criterion would mean less energy production in a given area and higher transport costs for the same amount of biomass (increasing distances). It is obvious that further study is required concerning land use.

Transport (TR):

- Tractors are assumed to be used for transport of biomass on the farmers' land. For transport of manure and biomass from other areas trucks are used.

Storage (ST):

- Investment costs are 800 times biogas production in Nm^3/h, based on [15].

Digester (DG):

- A one-stage, CSTR (Continuously Stirred Tank Reactor), mesophylic digester is assumed.
- The methane content of the biogas is calculated based on methane production potentials of the manure and maize.

Digestate (DS):

- The digestate is assumed to have a commercial value as fertilizer. Besides that, digestate must be used as fertilizer because of sustainability reasons. This is discussed in section 3.2.3.
- The amount of digestate which is allowed on the land is determined by maximum values for nitrogen and phosphate. If extra fertilizer is needed by the crops, this needs to be supplied by artificial fertilizer.

Upgrading (UP):

- In our research it is assumed that the upgrading installation is at the same location as the biogas plant, so no extra transport of biogas is needed.
- The chosen upgrading technique is water wash. This is not only a commonly used technology, but it also gives the opportunity to remove the CO_2 to a specified level. In our case, we desire the green gas to have a similar Wobbe-index as Dutch natural gas, i.e. a CH_4 content of 89.4 %. Further, it is assumed that 3 % of the CH_4 in the biogas is lost during the upgrading process, i.e. the methane efficiency is 97 %.

Injection (IN):

- Concerning injection, we assume a more or less arbitrary 500 m pipeline connection between the upgrading installation and a distribution grid injection point. The green gas is compressed to 8 bar. Furthermore, it is assumed that the grid can handle the green gas flow without limitations.

Item	Data	Reference
MN: Manure		
Manure production dairy cattle	20 t/(animal·a)	[10], [11]
Manure price	-15 €/t	[12]
BM: Biomass		
Agricultural land in Friesland, Groningen, Drenthe	32.5 %	
Agricultural land used for energy maize	25 %	
Nitrogen use limit maize	150 kg/ha	Dutch legislation
Phosphate use limit maize	75 kg/ha	Dutch legislation
Savings on fertilizer	3 €/t digestate	Commercial price
Crop yield silage maize	45 t/ha	[4], [13], [14]
Maize price	28 €/t	[15], [16], [17]
TR: Transport		
Capacity tractor (biomass)	30 m^3 (14 t)	[18], [19]
Capacity truck (manure & biomass)	30 t (100 m^3)	[18], [19]
Transport costs tractor	0,85 €/km	[20]
Transport costs truck	1,24 €/km	[20]
Energy consumption tractor transport	2.1 MJ/(t·km)	[18]
Energy consumption truck transport	1.3 MJ/(t·km)	[18]
DG: Digester		
Biogas yield cow manure	25 Nm^3/t	[11], [21], [22]
Biogas yield silage maize	175 Nm^3/t	[4], [22]
Methane content biogas	55.6 vol%	[21]
Investment cost function	$0.0082*Q^{0.9042}*10^6$	Based on [15]*
DS: Digestate handling		
Max. nitrogen from digestate on land	170 kg/ha	Dutch legislation
Max. phosphate from digestate on land	75 kg/ha	Dutch legislation
UP: Upgrading		
Upgrading method	Water wash	
CH_4 efficiency	97 %	[23]
CH_4 content green gas	89.4 vol%	
Investment cost function upgrading	$81532*Q^{0.4551}$	Based on [15]*
IN: Injection		
Distance installation to grid	500 m	

Piping costs	130 €/m	[24]
General		
Depreciation	12 years	SDE (Dutch subsidy regime)
Interest rate	7 %/a	SDE (Dutch subsidy regime)
Operating hours installations	8000 h/a	[12], [24]
Electricity price	14 €ct/kWh (from grid)	Commercial price

Table 3.1: Used data for cost price calculation.
** Q = biogas production (Nm^3/h).*

3.2.2 Costs

In an economic analysis of biogas production in Ireland a sensitivity analysis was needed to identify the economic parameters which are most critical to economic feasibility [26]. The price of biomethane and the cost of feedstock turned out to be the most critical, while overall capital and operating costs were less significant.

In our study the costs will also be divided into capital and operating costs. The data for this calculation are collected from literature and personal communication. The depreciation and interest rate correspond to the Dutch subsidy regime. Investment costs for plants as a function of scale were analyzed by putting data from literature in a spreadsheet and interpolating the data points by a function of the type $y = a \cdot x^b + c$ with an R-squared value of at least 0.9. The total cost price of one Nm^3 green gas is divided into costs for the transformation blocks as shown in Figure 3.1. In this way it is possible to check the hypothesis that the total costs will decrease with increasing scale, but transport costs will increase.

The chosen scale of green gas production is between a small production plant 100 Nm^3 (~170 Nm^3 biogas) and 1200 Nm^3 (~2000 Nm^3 biogas). The latter represents a large scale plant which is currently under development in The Netherlands.

3.2.3 Sustainability

Researchers seem to use different criteria to assess the sustainability of processes. It was shown that the energy input into (large-scale) biogas systems corresponds to 20-40 % of the energy content in the biogas produced, but no conclusions were drawn what this means in terms of sustainability [27]. Emissions (CO_2, CO, NO_x, SO_2, HC, CH_4 and particles) of biogas systems were analyzed from a life-cycle perspective for different biogas systems based on different raw materials [28, 29]. A general conclusion was that biogas systems normally lead to environmental improvements. This is often due to indirect environmental benefits of changed land use and handling of organic waste products (e.g. reduced nitrogen leaching, emissions of ammonia and methane), which often exceed the direct environment benefits of replacing fossil fuels by biogas (e.g. reduced emissions of CO_2 and air pollutants). Gerin et al. [30] confined their study to the energy and CO_2 balance as the core of calculating specific green certificates, but recognized that a more general assessment of sustainability should include other issues, e.g. other greenhouse gases, energy needed for seed, machine and plant production, etcetera. Vetter et al. [31] investigated, besides the CO_2 balance of a green gas chain, the humus balance, erosion effects and biodiversity of biomass production for this chain. Another study discussed the assessment of sustainability as well, but was confined to land-use systems [32]. Yet another study chose a different way for assessing the sustainability of energy production from grassland [9]. In the integrative sustainability concept they followed, no prior distinction is made between economic, environmental and social dimensions. From this concept seven substantial preconditions for sustainable development were derived:

i. Sharing the use of natural resources fairly.
ii. Sustainable use of non-renewable resources.
iii. Sustainable use of the environment as a sink.
iv. Protection of human health.
v. Sustainable use of renewable sources.
vi. Conservation of the cultural function of nature.
vii. Securing an autonomous existence (e.g. employment, securing wages).

Based on these objectives, 16 indicators were chosen which were quantified as much as possible.

In The Netherlands six themes were proposed to assess sustainability for biomass production, which show many similarities with the objectives mentioned above [33]. The first three are specific for biomass; the last three resemble the more general triple P (people, planet, profit). In this approach it is not known beforehand where in the world this biomass is produced, which make that the criteria have a general character, although it is assumed that the biomass is used in The Netherlands. This enables us to relate them to a scale factor in a later stage (because of the focus of our research). We chose to take these six themes as a basis. This choice is due to the Dutch setting of our research, and is in good correspondence with the aforementioned literature. Moreover, the Dutch green gas certificate trade is based on these criteria (under development). The themes with indicators and quantification are shown in Table 3.2. The quantified indicators are marked by a bold letter. Some additions were made concerning the quantitative indicators where appropriate.

Theme	**Indicator**	**Quantification (prescribed)**	**Quantification (added by authors)**
Greenhouse gas balance	Net emission reduction when compared to fossil energy, including application (i.e. measured for the total supply chain).	At least 50 % (**a**).	-
Competition with food, local energy supply, medicine and construction materials	Availability of biomass for food, local energy supply, construction materials or medicine should not decrease.	Not available.	25 % of farm land used for energy production (**b**). Energy needed for production and grid injection of one Nm^3 green gas should not exceed the energy content (higher heating value) of one Nm^3 green gas (**c**).
Bio diversity	No deterioration of protected areas or valuable ecosystems.	Plantations should not be in or near protected areas. Reference year for wood feedstock is 1994 (FSC 10.9), for palm oil 2005 (RSPO 7.3), for others 2006. (**d**)	-
	Knowledge about active protection of the local system.	Management plan for active protection of local ecosystem (**e**).	-
Profit	No negative effects on local and regional economy.	Not available.	-
	Knowledge about active contribution to improving of local economy.	Report required about active contribution to improving of local economy. Transparent communication with local population is demanded (**f**).	-
Prosperity (no negative effects on the well-being of employees and local population)	Working circumstances of employees.	Complying Social Accountability 8000 and Tripartite Declaration of Principles concerning Multinational Enterprises and Social Policy as indicated by the International Labour Organization (**g**).	-
	Human rights.	Complying Universal	-

		Declaration of Human Rights (concerning: non-discrimination, freedom of association, child labor, forced and compulsory labor, disciplinary practices, security practices and indigenous rights) (**h**).	
	Property and user rights.	No land use without agreement of sufficiently informed original users (**i**). Land use is described in detail and officially approved (**j**). Official property and use of population is respected (FSC 3) (**k**).	-
	Social circumstances of local population (active contribution to improvement).	Not available.	Odor (**l**). No. of transport movements (**m**).
	Integrity.	Companies in the supply chain comply the Business Principles for Countering Bribery (**n**).	-
Environment	Waste management.	Comply local and national laws Apply Good Agricultural Practice guidelines on integrated crop management.	The mass of co-substrate should not exceed the mass of manure. (**o**).*
	Use of agricultural chemicals (including artificial fertilizer).	Local, international and EU law.	Cycles of carbon and nutrients (**p**).**
	Preventing erosion and exhaustion of soil.	Not available.	-
	Active improvement of quality and quantity of surface and underground water.	Not available.	-
	Emissions into air.	EU laws.	NO_x, SO_x, N_2O, NH_3 specific (**q**).

Table 3.2: Identified criteria for sustainability.

** Dutch legislation on fertilization.*

*** As much as possible. This is also determined by Dutch legislation.*

The interdependency between sustainability and scale is evident. When biogas production is still relatively small scale in The Netherlands, criteria concerning economy and prosperity in developing countries are not really relevant. This might change significantly when production is scaled up and biomass is imported from abroad. Also, with small scale biomass usage, waste flows or energy crops on fallow lying land could be used. On small scale this will have no impact on matters like biodiversity. But up-scaling biomass production might cause problems in this respect, if that means that relatively more land will be used for one type of biomass.

Concerning criterion (a), it is not integrated in our model, but calculations point out that a biogas supply chain based on digestion meets this requirement [12]. And also that the emission of greenhouse gases can be reduced by some 75 % when biogas replaces fuel oil in district heating plants or petrol in light-duty vehicles, despite the fact that the emission from vehicles, etc. used in biogas production is included [6].

In our approach the criteria (b), (o), (p) and (q) are incorporated in the calculation model, i.e. results of the model always meet these criteria. The preference of using digestate as a fertilizer (criterion (p)) from a sustainability point of view was also shown by [31].

Just like (b), criterion (c) is somewhat arbitrary. One might argue that it does not matter how much energy is needed for producing green gas when the used energy is sustainable as well. But even in this case land is needed for producing energy. This land could be used for producing food as well. Energy needed for fodder which is transformed into manure is not incorporated in the model, because the manure is considered a stream which is available anyway. Embodied energy in biomass storage facilities are considered to be negligible.
Criteria (d), (e), (f), (g), (h), (i), (j), (k), (l) and (n) are relevant, but can be neglected at the scale considered in this study, because these criteria concern mainly social circumstances in developing countries or comprise management activities by biogas producers.

Criterion (l), odor, can be considered a problem in general, but is very subjective. The closer to populated areas, the more this is considered a problem. We assume this negligible, as the digester is on a farm.

Criterion (m), number of transport movements, has shown to be a barrier in practice, considering the resistance by people living in the neighborhood of new biogas installations. One truck movement is defined as a truck driving to and from the installation. The number of allowable transport movements is difficult to assess in respect to sustainability. At the moment we consider this a political decision. As a rough estimation it could be stated that truck movements are possible during 250 (working) days a year. With 8 working hours on each day and one allowed transport movement per hour this would be 2000 allowed transport movements per year.

3.3 RESULTS

3.3.1 Costs

The results, including the total cost price of one Nm^3 of green gas, are shown in Figure 3.2. In this Figure it is shown that the total cost price of one Nm^3 green gas at a production rate of 100 Nm^3/h is significantly higher than when producing 1200 Nm^3/hr. Costs per Nm^3 of biomass and manure remain constant with increasing scale. Costs of transport and digestate slightly increase, while costs for storage, digesting, upgrading and injection decrease. A subdivision of relative costs at 150 Nm^3/h, 300 Nm^3/h (which is a little above the average for The Netherlands) and 1200 Nm^3/h is shown in Figure 3.3.

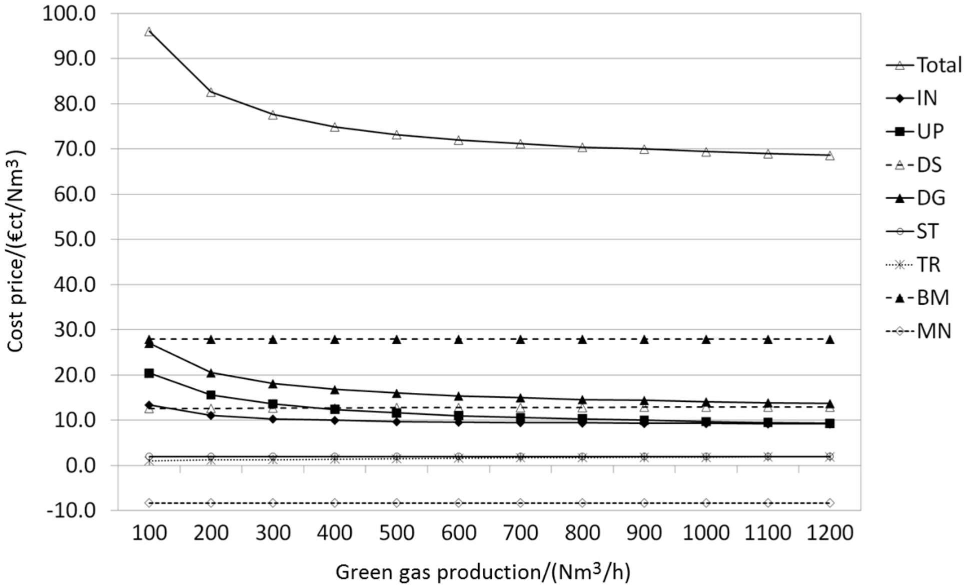

Figure 3.2: Cost price of green gas (MN = manure, BM = biomass, TR = transport, ST = storage, DG = digester, DS = digestate, UP = upgrading, IN = injection).

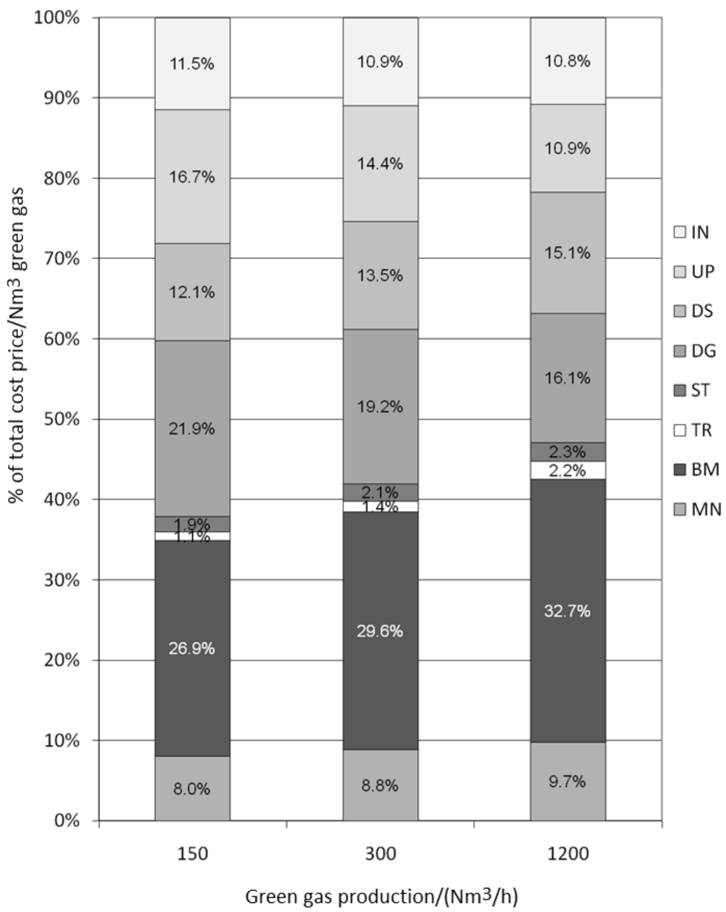

Figure 3.3: Subdivision of relative costs at a green gas production rate of 150, 300 and 1200 Nm^3/h. The total costs for these production rates are 87.2 €ct/Nm^3 (at 150 Nm^3/h), 77.6 €ct/Nm^3 (at 300 Nm^3/h) and 68.6 €ct/Nm^3 (at 1200 Nm^3/h). Although the cost price for manure (MN) is negative, the value is shown as a positive value for presentation reasons.

3.3.2 Sustainability

As stated before, several criteria are automatically fulfilled by incorporating them into the model. The number of transport movements is mentioned as a criterion for sustainability. The relation between scale and transport movements is shown in Figure 3.4.

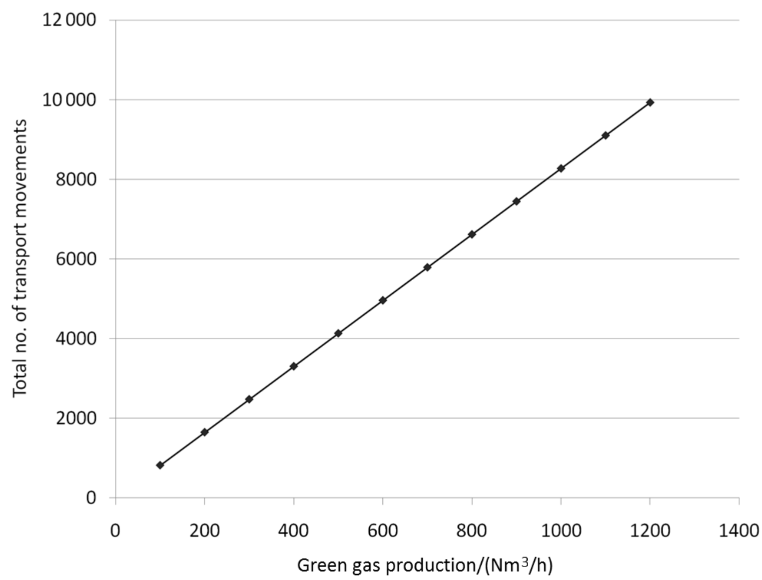

Figure 3.4: Total number of transport movements. The needed transport for removal of digestate is included.

With the aforementioned fictitious limit on transport movements of 2000 per annum the transition point from sustainable to non-sustainable is at some 250 Nm^3/h. See Figure 3.5[1] for the energy consideration, at all scales the energy need is below the given limit (c) in Table 3.2. A subdivision of energy need at 150 Nm^3/h, 300 Nm^3/h and 1200 Nm^3/h is shown in Table 3.3. In this Table can be seen that the energy need is determined to a great extent by digestion and upgrading. The share of transport increases with increasing scale.

[1] Figures 3.5 and 3.7 and Table 3.3 differ from the ones published in Eng. Life Sc. The publication version contained an error in the equation for energy need and is corrected in this thesis.

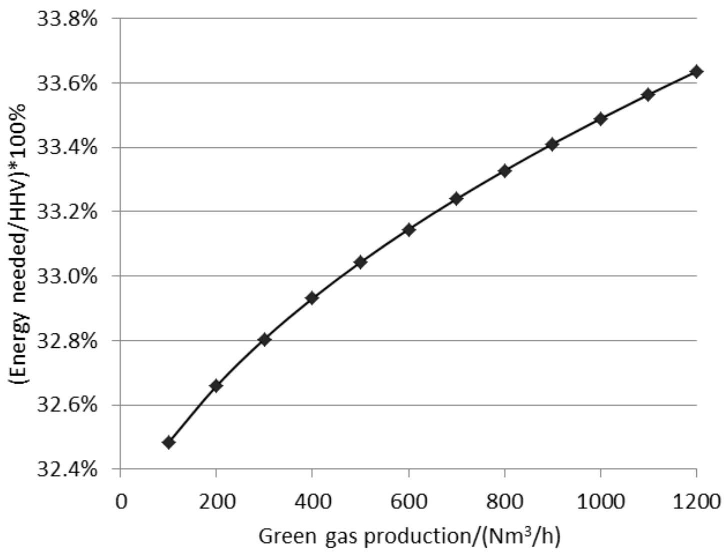

Figure 3.5: The ratio of the needed energy for the production and injection of one Nm^3 green gas and the higher heating value (HHV) of green gas. In the model the HHV of green gas is 39.8 MJ/Nm^3.

Green gas production/(Nm^3/h)	**BM**	**TR**	**DG**	**DS**	**UP**	**IN**	**Total**
150	16.5 %	1.5 %	39.4 %	10.5 %	31.3 %	0.8 %	100 %
300	16.4 %	2.1 %	39.1 %	10.7 %	31.1 %	0.8 %	100 %
1200	16.0 %	4.0 %	38.0 %	11.4 %	30.3 %	0.8 %	100 %

Table 3.3: Subdivision of energy need for producing green gas (injected into the gas grid) for three production capacities (150, 300 and 1200 Nm^3/h).

3.4 DISCUSSION

To check the calculations, a comparison was made with a reference calculation [12]. In this reference a cost price for green gas was calculated on the basis of a water wash upgrading system. The required heat necessary for this technology is supplied by burning biogas in a boiler. The surplus heat from gas washing is sufficient for heating the digester. A mass reduction of 10 % by digestion is assumed. In Table 3.4 data of a relatively small system are given (270 Nm^3/h biogas or 150 Nm^3/h green gas).

Item	Data
Biomass and Manure	
Trade value manure	-15 €/t
Co-substrate type	50 % energy maize and 50 % biomass with lower costs (waste products, sometimes less energy content)
Cost price co-substrate	23 €/t
Transport and Storage	
Costs transport manure	5 €/t
Digester	
Operating hours	8000 h/a
Investment	4490 €/(Nm^3/h) biogas
Fixed O&M-costs	295 €/(Nm^3/h) biogas
Energetic efficiency digester	67 %
Methane content biogas	56 %
Upgrading	
Upgrading technique	Water wash
Investment	3880 €/(Nm^3/h) biogas
Fixed O&M costs	385 €/(Nm^3/h) biogas]
Methane efficiency gas cleaning	99.9 %
General	
Electricity price	14 €ct/kWh (from grid)
Reference scale	270 Nm^3/h green gas
Depreciation	12 years

Table 3.4: Data of the reference system for production of green gas based on co-digestion of manure and biomass [12].

With these data the calculated cost price for green gas injection is 81.3 €ct/Nm^3 for 2010 (without the Dutch energy investment subsidy). The corresponding cost price in our model is 87,2 €ct/Nm^3. The main reason for this difference is that the reference model assumes a co-substrate price of 23 €/t, where we assume 35 €/t.

Figures 3.2 and 3.3 show that the more decentralized the biogas plants are, i.e. relatively small gas production rates, the more relevant the costs for digesting and upgrading are. On the other hand, relative costs for biomass and transport increase with increasing scale. For small scale, the cost price of green gas is high, but sustainability criteria hinder upscaling. A positive influence of lower biomass prices is evident [26], but this is determined by the market. Possibilities for minimizing the green gas cost price might be found in increasing biogas production in digesters or lowering the investment costs for digesters. A sensitivity analysis of these can be found in Figure 3.6. It seems that optimizing biogas production is more promising than decreasing the plant costs. Possibilities for moving the sustainability limits to larger scales, are minimizing the energy use of trucks and again biogas production, see Figure 3.7. Especially optimizing biogas production seems to be promising. Minimization the energy use of vehicles is an autonomous development.

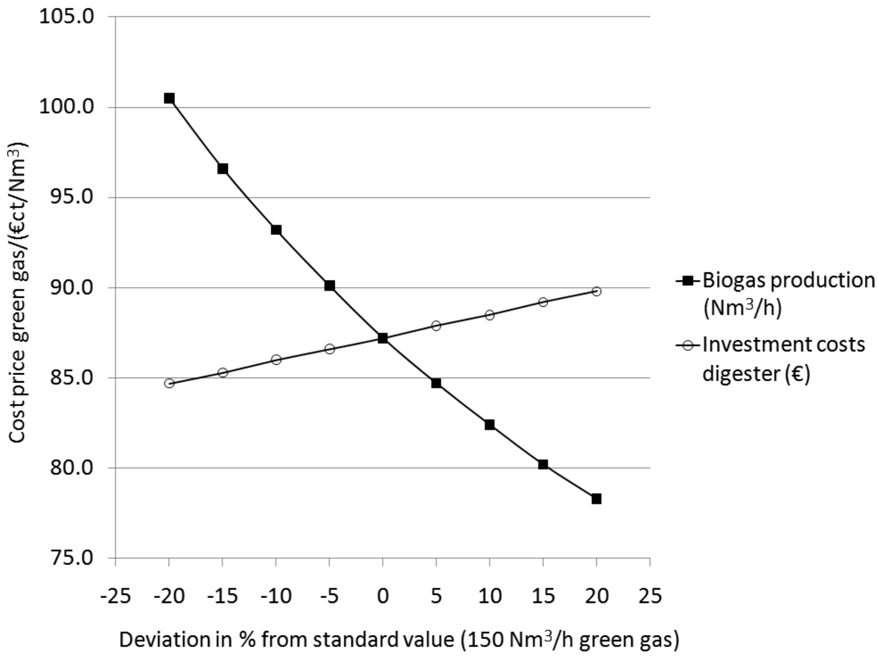

Figure 3.6: Influence of deviations in digester efficiency (biogas production) and investment costs of a digester on the cost price of green gas (the cost price at the standard value is 87.2 €ct/Nm^3).

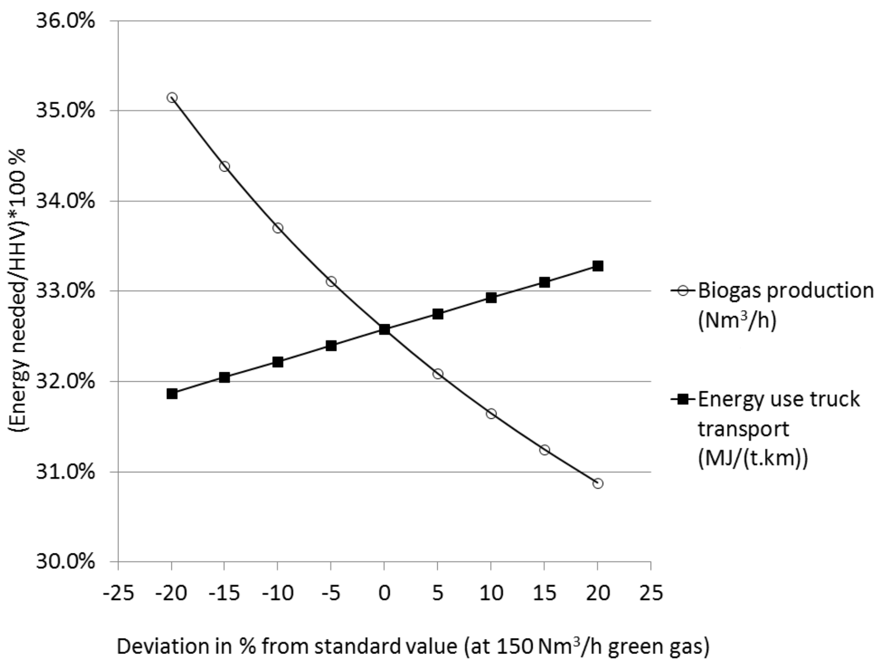

Figure 3.7: Influence of deviations in digester efficiency (biogas production) and the energy consumption of trucks on the total energy efficiency of a green gas chain (i.e. the energy needed for producing 1 Nm^3 green gas / HHV of green gas).

It was stated before that a green gas production based on co-digestion in The Netherlands has an envisioned potential of 1500 million Nm^3 per year [16]. In our model the green gas production would be 1350 Nm^3 per hectare agricultural area. With the aforementioned agricultural area of 267 973 ha the potential would be 362 million Nm^3 in the three northern provinces of The Netherlands. These three provinces cover approximately 25 % of the Dutch land area, but consist of relatively much agricultural land. So, even with the optimistic assumption of 25 % agricultural land-use for green gas production this target would be very hard to achieve.

3.5 CONCLUSIONS – FUTURE RESEARCH

In this research a reference green gas supply chain was analyzed. Energy maize was taken as co-substrate for digestion. It was found that transport costs increase with increasing volume of green gas, and that digester, upgrading and injection costs decrease with increasing scale. A more detailed analysis may be useful in order to find out which other biomass types are useful as a co-substrate and if an optimal substrate mix can be calculated in a given situation. If the maximum of 2000 transport movements were to be taken as a strict limit, the focus should be on decentralized, relatively small scale energy production systems. This would mean that digesters and upgrading installations should become cheaper and the efficiency should increase. Especially from developments in upgrading techniques a lot is expected. Research into increasing biogas output of digesters is promising in this respect as well. The presented research is based on a model which describes the throughput of a gas supply chain which is a quasi-static way of describing the supply chain. The next step is to optimize the model in the sense of matching supply and demand, i.e. dynamic simulation of a green gas supply chain. The objective of such an optimization should be to find ways to further decrease costs.

Transport movements can be considered a sustainability item with regard to quality of life. However, it is difficult to find a strict limit for the allowed number of transport movements. Above an estimation of truck movements is given. Determining the allowable number of movements might be more a matter of policy than science. On sustainability in general, more comments could be made as well. In this article we referenced to several studies on this subject. It seems that scientists as well as policy makers are still searching for sound sustainability criteria. Sound criteria on environmental indicators like 'preventing erosion and exhaustion of soil' and 'active improvement of quality and quantity of surface and underground water' are still lacking. The Cradle-to-Cradle approach might give some interesting new insights in this respect [34]. We believe that the kind of research we present here is still under development. This might influence the results and the most optimal scale of sustainable energy installations as well.

In this research we assumed the necessity of fully upgrading biogas to natural gas standards. Further research might show that this is not always necessary. The possibilities of mixing off-spec gas with natural gas in terms of economics should be investigated. Preconditions for mixing would depend on composition of the gas, the ratio of gases to be mixed and the requirements on the mixture. Finally, expanding the model to describe a regional situation with more than one digester is interesting with regard to finding optimal logistics.

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4

BALANCING GAS SUPPLY AND DEMAND WITH A SUSTAINABLE GAS SUPPLY CHAIN – A STUDY BASED ON FIELD DATA

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Abstract

The possibilities of balancing gas supply and demand with a green gas supply chain were analyzed. The considered supply chain is based on co-digestion of cow manure and maize, the produced biogas is upgraded to (Dutch) natural gas standards. The applicability of modeling yearly gas demand data in a geographical region by Fourier analysis was investigated. For a sine shape gas demand, three scenarios were further investigated: varying biogas production in time, adding gas storage to a supply chain, and adding a second digester to the supply chain which is assumed to be switched off during the summer months. A regional gas demand modeled by a sine function is reasonable for

household type of users as well as for business areas, or a mixture of those. Of the considered scenarios, gas storage is by far the most expensive. When gas demand has to be met by a green gas supply chain, flexible biogas production is an interesting option. Further research in this direction might open interesting pathways to sustainable gas supply chains.

4.1 INTRODUCTION

The current share of renewable energy in the total energy consumption in The Netherlands increased from 3.8 % in 2010 to 4.2 % in 2011. This is caused by an increase in renewable energy consumption as well as a decrease of the total energy consumption. About 75 % of this share in 2011 has a biomass origin [1]. The Dutch government aims at a renewable energy share of 14 % in 2020. The current share of green gas in the Dutch gas consumption is estimated to be about 1 %. Published ambitions envision a share of 8-12 % of green gas in 2020 [2]. It is evident that green gas can play an important role in achieving the renewable energy goals. Therefore, several studies have been carried out to investigate the possibilities of injection of green gas into the gas grid ([3], [4], [5]). The possibilities of 12 % natural gas replacement in 2020 and 20 % in 2030 were investigated [3]. In these studies a constant production of green gas in time is assumed. There seem to be good opportunities but:

- A continuous 12 % replacement of natural gas by green gas during a year seems not to be possible without taking measures. A number of hours a year the minimum gas demand is lower than the (theoretically) constant production of digesters, which implies overproduction.
- In some regions, digesting all available manure could deliver more green gas than can be injected into the gas grid during a period a year (again, under the assumption of constant production). In general, the studies indicate that the biomass availability is high enough to achieve a higher natural gas replacement than is currently the case.

Thus, the target for injection of green gas is higher than current practice and the availability of biomass offers possibilities to increase the share of green gas in the total gas consumption.

Usual analyses of biogas systems consider its production to be constant in time. Constant production, upgrading to natural gas quality and injection into the grid has a decreasing cost price per produced Nm^3 when scale is increased. This is caused by decreasing investment costs of digesting, upgrading and injection per Nm^3 green gas as the production rate increases.

However, gas demand (i.e., the gas consumption by end users) varies with time, not only on a daily basis but also on a seasonal basis. From a technical point of view a constant green gas production and injection should not exceed the minimum gas demand in the grid into which the gas is injected. The pressure in the grid would become too high. This minimum gas demand might for instance occur on a warm July night. The usually suggested solution for a higher gas production than gas demand is gas storage, connection of gas distribution grids or compression and injection into the gas transport grid. It is not always clear what storage technology should be used under which circumstances. Neither is it clear whether a development in a more flexible biogas production, i.e. a higher production rate in winter and a lower production rate in summer, would increase the annual gas production quantity such, that the cost price of green gas (€ct/Nm^3) decreases and more natural gas replacement is possible. As digestion of biomass is a biological process, the predominant opinion is that the process should be kept stable and changing operational parameters should be done carefully [6]. On the other hand, it is also known that farmers sometimes add glycerin to boost the production or re-enter digestate in the digester if production must be limited. Chances for operating one or more extra digesters to meet the gas demand only during some months a year when gas demand is high are not explored yet to the current knowledge of the authors. Exploring these options would enhance the understanding of the possibilities of green gas in our gas supply, both technical and economic.

These considerations raise the following research question: What would be the cost price of green gas as a function of scale, when the seasonal (fluctuation in the) gas demand should be met by a green gas supply chain?

The following sub questions are derived from this research question:

1. How can a seasonal gas demand be modeled as a mathematical description which is sufficiently accurate?
2. How can a green gas supply chain be designed to be flexible to meet the varying gas demand? At this point three scenarios for investigation are distinguished:
   - Varying the gas production of a digester such that the seasonal swing in gas demand is met. In this scenario no gas storage is taken into account.
   - Incorporating a gas storage facility into the supply chain with constant gas production, such that, in case of overproduction, excess gas can be stored.

- A digester is added parallel to the digester already available at constant production, with the intention to 'switch on and off' the extra digester.

3. Given a gas demand pattern in a geographical region, can verdicts be done about optimal locations for digesters, i.e. is location planning a tool to establish a better fit between supply and demand? Optimal in this respect should be interpreted as the lowest cost price within defined sustainability criteria.

In section 4.2 we discuss our approach to answer these questions. In section 4.3 the results of our simulations are presented and in section 4.4 we discuss the results after which the conclusions are presented in section 4.5.

4.2 METHOD AND ASSUMPTIONS

Sub question 1 - Modeling gas demand

In general, annual gas demand in a defined geographical region can be characterized by a minimum and a maximum gas demand and the way it alters during a year. The total annual demand divided by 8760 hours gives the average hourly gas demand.

Schouten et al. [7] addressed the uncertainty in gas demand with a linear function which relates gas consumption in The Netherlands to the outdoor temperature, corrected for wind speed. Gas demand remains constant when the outdoor temperature is above a limit value. This relation between outdoor temperature and gas demand holds for households. However, the demand of (large) companies is not necessarily directly related to outdoor temperature while they may be connected to the same gas receiving station (GRS). Bärnthaler et al. [8] used specific user data to define a gas demand pattern of households, specific types of companies (bakery, laundry) and a mixture of those. It is evident that the gas demand is greatly dependent on the type of gas consumer.

In our study, we used actual gas demand data from September 2009 to September 2010 of six Gas Receiving Stations (GRS's) in the north of The Netherlands. This gave us the opportunity to get a more or less general insight in field data of gas demand of households and companies in an anonymous way. The data were supplied by Rendo, a Dutch gas Distribution System Operator (DSO). Similar information on gas demand can be found in Donders et al. [4] and Smits et al. [5]. Sixteen cases were extracted from the supplied data, see Table 4.1. A distinction between small-scale and large-scale users was derived from the data. A small-scale user is an end user with an annual gas demand smaller than 170 000 Nm^3. A large-scale user is an end user with a minimum annual gas demand of

170 000 Nm^3. Large-scale users were confirmed to be companies on business areas, whereas small-scale users are mainly households, possibly combined with small or medium-sized companies. For every GRS a concise description is given on the type of users, the total annual gas demand, and the measured minimum and maximum hourly demand. A GRS in 'island operation' means that the grid under consideration is not interconnected to another GRS, thus that the natural gas in this distribution grid only enters via the GRS. Especially cases 5 and 6a are interesting because they are opposites in terms of end users: a small village representing almost only households and a business area without households respectively. For each region the hourly gas demand was available.

In order to be able to mathematically describe a seasonal gas demand, the data must be transformed into a continuous and periodic function. In this research, this was done for all cases by producing a sine function using Fourier analysis. As an example, the data and the corresponding sine function of case 5 are presented in Figure 4.1. This Figure shows that, roughly between hours 7500 and 8500, the sine function is permanently below the measured data. This holds for all cases. This was accepted for this study, it can be considered to be a worst case. In practice the difference between maximum and minimum demand will be smaller.

Case no.	GRS no.	Properties/description	Total gas demand (Nm^3)	Average gas demand (Nm^3/h)	Minimum gas demand (Nm^3/h)	Maximum gas demand (Nm^3/h)	Remarks
1	1	1 small and 1 large village with relatively large business area including 5 large-scale users. No. connections: 7100 (incl. 5 large-scale users).	25 921 352	2959	498	10 872	'Island' operation
1a	1	Only large-scale users of GRS 1.	6 713 454	766	41	1417	
1b	1	Only small-scale users of GRS 1.	19 207 898	2193	32	9639	
2	2	Village with small-scale industry incl. 2 large-scale users No. connections: 2100 (incl. 2 large-scale users).	5 556 040	634	0	2981	Coupled to 8 bar grid
2a	2	Only large-scale users of GRS 2.	1 854 707	212	0	599	
2b	2	Only small-scale users of GRS 2.	3 701 333	423	0	2571	
3	3	Village with large business area incl. 15 large-scale users No. connections: 7200 (incl. 15 large-scale users).	31 356 080	3579	308	12 150	'Island' operation
3a	3	Only large-scale users of GRS 3.	12 715 179	1452	71	3421	
3b	3	Only small-scale users of GRS 3.	18 640 901	2128	98	9427	
4	4	Village with small-scale business area (including 2 large-scale users). No. connections: 2300 (incl. 2 large-scale users).	8 346 280	953	0	3987	Coupled to 4 bar grid
4a	4	Only large-scale users of GRS 4.	3 042 831	347	42	963	
4b	4	Only small-scale users of GRS 4.	5 303 449	605	0	3184	
5	5	Village with small business area (no large-scale users). No. connections: 2000.	8 589 842	981	26	3610	'Island' operation
6	6	Large village with large-scale business area with 26 large-scale users. No. connections: 22400 (incl. 26 large-scale users).	62 359 454	7119	758	29 650	Fed by 2 GRS's
6a	6	Only large-scale users of case GRS 6.	14 981 612	1710	273	5182	
6b	6	Only small-scale users of case GRS 6.	47 377 842	5408	130	24 468	

Table 4.1: Cases of which the gas demand is analyzed. See text for an explanation of terminology.

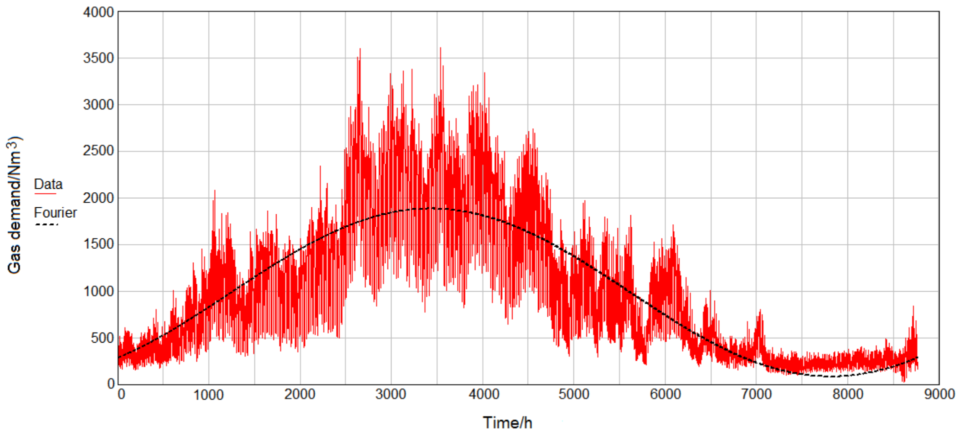

Figure 4.1: The annual gas demand of case 5: Measured data (8760 hours) and the same measured data represented by a sine function. Properties sine function: average 981 Nm^3/h, max. 1888 Nm^3/h, min. 81 Nm^3/h.

In order to check whether this curve sufficiently accurately describes the seasonal fluctuating gas demand, we pose that it is not necessary to determine an hourly deviation. If we assume that daily variations in gas demand can be overcome by the standard gas storage on top of a digester, and that the gas supply chain is able to follow the curve one way or another, then, at least in this stage of our research, we accept the sine curve to be sufficiently accurate. To check the validity of this assumption an estimated needed daily biogas storage for every day d as a percentage of the average daily production was calculated with

$$Storage\ percentage\ (d) = \frac{storage\ need\ (d)}{average\ daily\ production} .100\%$$

where the daily storage need was approximated for every day (365 days) by taking the difference between production and demand for every hour each day (24 h) and summing the differences for all hours where production was larger than the demand. This overproduction, which can be considered to be a worst case situation, has to be stored. The average daily production was chosen under the assumption that this would depict the size of a digester with daily storage facility. The results are shown in Figure 4.2 for case 5.

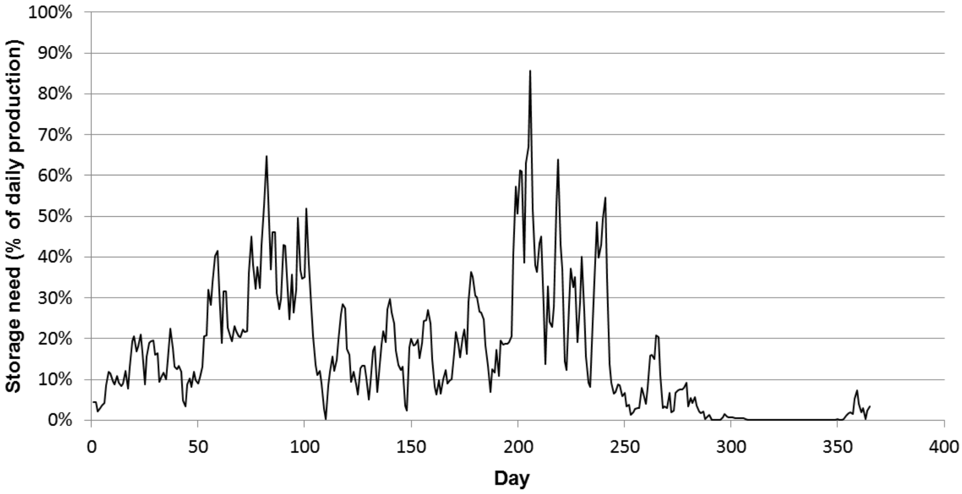

Figure 4.2: Storage need on a daily basis (case 5).

The maximum storage need was found to be 86 % and the average 16 % of the average daily biogas production. The storage need seems to be larger in spring and autumn than in summer and winter. The daily storage needs for all cases are depicted in Table 4.2. The maximum daily storage need was found to be 113 %. Often recommended are biogas holders which can take the daily biogas production of the plant in order to prevent trouble in unexpected situations. E.g., in sewage treatment plants, the size of the sewage gas holder normally varies between 0.75 and 1.5 times the daily produced biogas quantity ([8], [9]). Also a storage need of approximately 30-75 % of the daily production is reported, when the biogas is used for electricity production ([9], [10], [11]). With this check the maximum daily storage need was considered to be reasonable and the Fourier transformations were accepted to be appropriate. The costs of daily storage are assumed to be included in the investment costs of the digester.

The Fourier transformation was done for all cases. To express the variability of gas demand during a year the Seasonal Swing Factor (SSF) was defined to be the maximum of the sine function divided by the minimum, i.e. the ratio between maximum and minimum gas demand in a region. With this definition SSF is a continuous variable and always equal to or larger than one. In the case of Figure 4.1 (case 5) the SSF is 1888/81=23.3. The SSF's of all cases are depicted in Table 4.2.

	Total GRS		Large Users		Small Users	
	Max. daily storage need (%)	SSF	Max. daily storage need (%)	SSF	Max. daily storage need (%)	SSF
GRS 1	94	8.8	90	1.2	n/a*	n/a*
GRS 2	113	11.2	92	1.3	n/a*	n/a*
GRS 3	75	6.8	87	1.8	n/a*	n/a*
GRS 4	n/a*	n/a*	56	5.2	n/a*	n/a*
GRS 5	86	23.3	n/a**	n/a**	86	23.3
GRS 6	91	20.2	61	3.2	n/a*	n/a*

Table 4.2: Seasonal Swing Factors (SSF) of the 6 GRS's: totals and subdivision in large and small users.

**   Data omitted because of inaccuracy of measurement.*

*** No large users exist for this GRS.*

It can be seen that in general, large users have a much lower SSF than small users. The SSF varies from some 1.2 for large scale users to up to above 20 for small scale users. This high value for small users reduces to approximately 12 when real data of the summer months are used instead of the minimum of the sine. Therefore, for our modeling purposes, SSF=2 might represent some (large) companies which show a rather low influence of outdoor temperature on gas demand. SSF=12 might represent a typical residential area. SSF=7 is an area which combines both and represents a mixture of houses and (large) companies. What a gas demand modeled by a sine function would mean for SSF=2, SSF=7 and SSF=12, is depicted in Figure 4.3. Note that the data were transformed to fit into a 8000 hours operational time in a year (instead of 8760 hours).

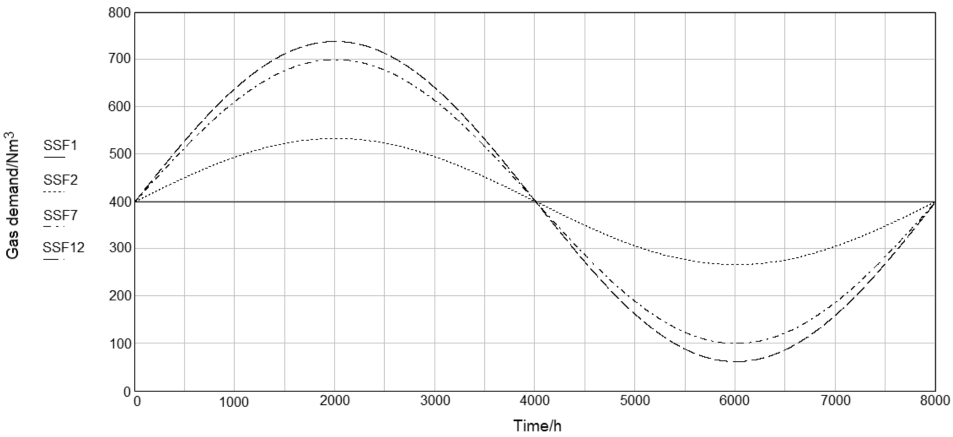

Figure 4.3: Generalized representation of gas demand data for three Seasonal Swing Factors. Note that SSF=1 means a constant demand during a year. The average 400 Nm^3 is chosen arbitrarily.

As the general form of the sine function is

$$f(t) = c_1 + c_2.sin\left(\frac{2\pi t}{8000}\right)$$

where c_1 is the average hourly gas demand (Nm^3/h, 400 in Figure 4.3) and c_2 is the amplitude (300 for SSF=7 in Figure 4.3), then c_2 can be expressed in terms of c_1 and SSF (for $0 < c_2 < c_1$) with basic mathematics:

$$SSF = \frac{c_1 + c_2}{c_1 - c_2}$$

or

$$c_2 = c_1.\frac{SSF - 1}{SSF + 1}$$

What it means to increase the SSF further can be analyzed by considering the limit of c_2 when SSF would reach infinity:

$$\lim_{SSF \to \infty} c_2 = c_1$$

which means that the maximum demand (and thus the maximum design capacity of an installation) in the model will never exceed twice the average demand.

Sub question 2 – Modeling the demand following capacity of supply chains

In our study we consider a green gas supply chain as shown in Figure 4.4.

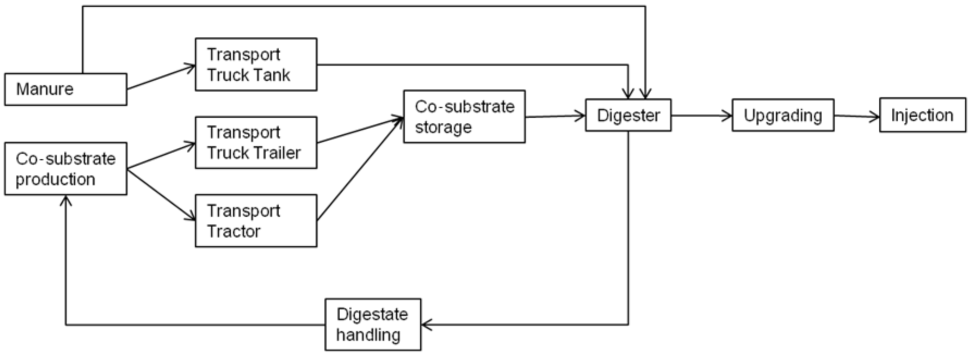

Figure 4.4: The considered green gas supply chain. An optional gas storage facility may be thought between Upgrading and Injection.

The considered supply chain is based on co-digestion of cow manure and maize as was previously analyzed by Bekkering et al. [12]. In this study it was assumed that the produced biogas is upgraded to Dutch natural gas quality and injected into the natural gas grid. The minimum scale of the modeled supply chain was 100 Nm^3/h green gas and the maximum scale 1200 Nm^3/h. One of the assumptions in this study was continuous, steady production of biogas, i.e. all flows in the chain were assumed to be constant, except production of maize, which was assumed to be harvested once a year after which it is stored. The assumptions depict a more or less static description of a sustainable gas supply chain. In the calculation model the needed amount of co-substrate requires a given geographical area for growing the co-substrate. The needed area is taken as a percentage of the total area. Sustainability criteria were implemented in the model, energy and CO_2 balance and the number of transport movements can be calculated. The cost price per Nm^3 was calculated on a project base. I.e., the net present value of each step was calculated and related to the amount of gas produced. Fixed prices per tonne for manure and co-substrate were used, and fixed costs per km per tonne for transport. Costs for digesting, upgrading and injection were calculated by using data of investment costs and taking a percentage of this for operational costs.

In the mentioned study it was shown that the cost price decrease at increasing scale is most significant at relatively small scales. Transport costs only slightly increase with increasing scale, see Figure 4.5. This supply chain serves as a starting point for the three scenarios.

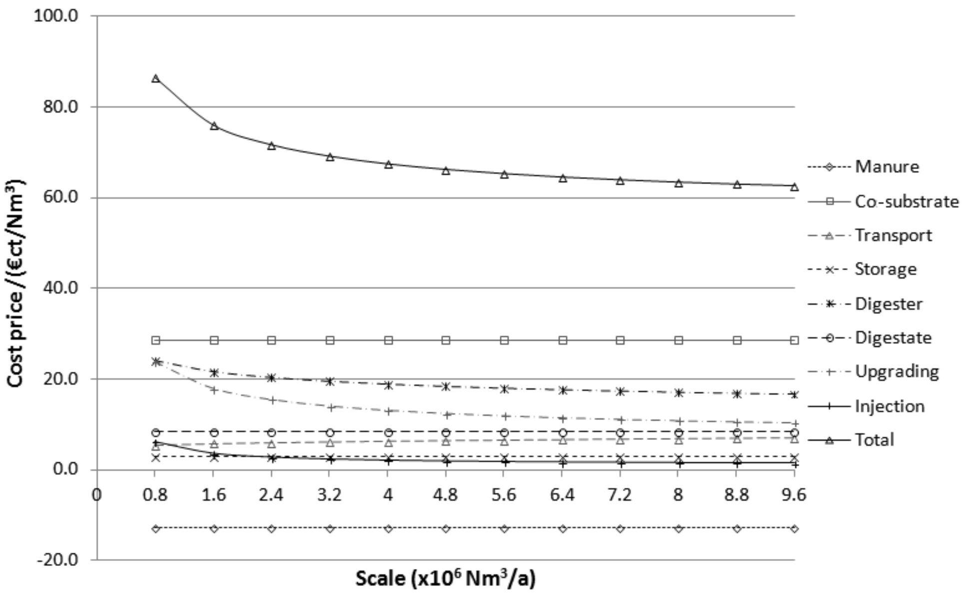

Figure 4.5: Cost price of green gas in relation to scale (adapted from [12]).

Scenario 1 – Flexible gas production chain

In this scenario it is assumed that green gas production and injection is able to follow the gas demand. In order to gain insight in possibilities for supply chain flexibility, for every block the possibilities in modeling the dynamic behavior have been investigated by literature study and surveys.

Manure:

Manure production depends on matters like grazing time, fodder type and amount of milk produced. Common practice is that costs and environmental effects are allocated to cattle farming and not to biogas production. Availability and duration of storage is an issue for our research. A farm with a grazing regime will have more manure available in storage in winter than in summer which is beneficial for the purposes of our study. This, together with the circumstance that manure can only be stored for a very short period [13], makes that we consider manure to be available at all times during the year for all SSF's.

Co-substrate production:

Harvest of co-substrates (maize) is assumed to happen once a year in the reference model, this implies storage need. In case of growing clover and grass for biogas, it is optimal from a economic point of view to harvest later than what is regarded as the normal harvest time of forage for milk production, since the lower biogas production per kg DM was compensated for by higher DM yield [14]. They investigated the logistics of forage harvest to biogas production. Their model included mowing, chopping, transport of the grass to storage and the ensiling process. An optimal date was calculated where the total harvest costs were lowest. Starting harvest 20 days earlier increased the total harvest costs by 2 %. Delaying the starting date with 10 days increased the total harvest costs by 14 %. Ten days earlier or later also decreased the harvest value (related to biogas production) with 2-3%. Prochnow et al. [15] investigated the biogas and methane yields per tonne VS of grass from landscape management as a function of cutting period. These yields decreased from June to February. This decrease is caused by an increasing crude fiber content which is less digestible. On the other hand, the DM content increases in the same time span which cause the biogas yield per ha to have a maximum in August-September. In this research the profitability was not calculated. The advantage of finding an optimal harvest period was supported by Bruni et al. [16]. It can be concluded that harvest preferably should take place within a defined time frame, which implies a co-substrate storage need. It might be interesting to investigate the possibilities of several crops a year where the crops are fed to the digester. Studies in this respect are not known to the authors. On the other hand, a suitable crop rotation system has to be kept in mind as well, e.g. Murphy and Power [17] investigated the possibilities for wheat, barley and sugar beet. In our study we took average values from literature for maize production [12] and are aware that optimizations in this respect are possible.

Transport (truck tank, truck trailer and tractor):

Keeping the capacity of chopping and transport sufficiently high to avoid idle time does not necessarily result in the lowest costs [14], since the cost of the extra transport capacity is not outweighed by lower timeliness costs due to a shortened harvest. This effect is enforced by theoretical lower storage costs when production and transport are done in a larger time frame. This effect is not part of our model.

Co-substrate storage:

Ensilage is the basic process for high moisture storage of co-substrates and is the storage type assumed in our model. Research on preservation and storage of energy crops as feedstock for anaerobic digestion is still in its infancy [18]. In general, prolonged storage (ensiled) causes considerable oDM losses. On the other hand, methane yield per kg oDM increases at longer storage [19]. In our model the costs of co-substrate storage are linear with the amount to be stored, i.e. if it would be possible to save on the amount of stored co-substrates by harvesting twice instead of once, the costs would decrease as well. On the other hand, costs of co-substrate storage are low in comparison to other steps in the supply chain. There is a strong relationship between optimization in co-substrate production, transport and storage.

Digester:
The current predominant opinion is that the feeding rate of digesters should not vary too much. In general, as a rule of thumb plants are often operated at 95 % of their design capacity. Paradoxically, commercial anaerobic digestion processes are often operated at well below their optimal performance due to a variety of factors [20]. Although no fixed numbers can be given, increasing the biogas production, based on a given substrate, with 5 % a week may be considered safe [6]. Actively changing the biogas production may be done by changing the loading rate (hydraulic retention time), the volume of biomass in the digester (keeping the retention time constant), changing substrates or changing the temperature. Bruni et al. [16] reports that methane output of fresh maize and maize silage is obtained in short time compared to more recalcitrant substrates such as manure or agricultural waste. Therefore, it might be used to meet seasonal needs of gas. When needed, maize can be used to boost or to down regulate the methane production replacing low-methane yield or high-methane yield substrates, respectively. The final methane yield was reported to be achieved after some 25 days in a batch process. Also [21] described differences in biogas production rate during the first days of digestion for different co-substrate types. They also investigated the possibilities of using neural networks to predict biogas production based on historical data. It is known that farmers ‘boost’ the biogas production by adding glycerin [22]. In that case, CH_4 content of biogas increases as well. Adding 3-6 % glycerin to a basis co-digestion mixture increased methane production with a factor 1.2-1.3 ([23],[24]). For these percentages, a higher biogas production was observed after some 20 days in a batch test. Digesting only pig manure with 6 % glycerin gave a threefold increase in methane yield. Lindorfer et al. [25] investigated the doubling of the organic loading rate in a two stage, agricultural digester with effluent storage. The hydraulic retention time was decreased correspondingly. A new steady state situation was achieved after approximately eight months. Biogas yield and methane yield, related to the organic loading of volatile solids, remained almost on the same level. However, the residual methane potential of the effluent multiplied by a factor of 10. Decreasing biogas production might be done by re-entering digestate into the

digester. Decrease in temperature of the digester causes a decrease in biogas production rate [9]. Meeting peak loads in gas demand by steering the biogas production rate was discussed by Loewen et al. [26]. They showed that biogas production of lab-scale fixed bed reactors increased within a few hours after a vigorous increase in substrate loading. In the future there may be possibilities to increase methane production from biogas by hydrogenation of the CO_2 produced [27]. Concluding, there are some possibilities for seasonal variation in biogas production. However, to which extent and the consequences for process stability need further research.

Upgrading and Injection:
Upgrading is considered to be a flexible process which easily follows changes in digester production. A water wash process is assumed in our study. This process is highly flexible, although a few hours are needed to get the gas on-spec if the system is switched on. A swing down to 25 % of the maximum throughput is possible. This corresponds to SSF=4.

As literature is rather limited in specifying the possibilities for flexible biogas production and upgrading in time, we chose to take the hypothetical approach. I.e., we assume in this scenario that biogas production, upgrading and injection are flexible and equal the gas demand. We also assumed that the co-substrate (maize) is harvested once a year and the needed amount each year is stored.

The investment costs for digester, upgrading and injection were set based on the maximum production rate, where after the cost price was based on the real (average) production. Green gas production rates larger than 1200 Nm^3/h were considered to be unrealistic and thus not applicable.

Scenario 2 – Constant gas production with gas storage
In this scenario, biogas production is assumed to be constant during the year. The annual production at each considered scale is divided by 8000 production hours, which gives the constant hourly production (Nm^3/h). During all hours where production is higher than demand, which is defined by a sine function, the produced green gas has to be stored. It would be possible to build a seasonal gas storage between digester and upgrading installation, but this seems not to be logical because much more volume is needed than in the case of storing green gas. In our study, we assumed that investments for storage are allocated to the considered supply chain. To a certain extent the gas grid could be used as a storage facility, see e.g. Keyaerts et al. [28]. This might be done at very low costs, but is not considered in our model. In this respect, our model can be considered to represent a

worst case. In general, storage facilities can be built as balloon type, equivalent to a gasholder above a digester which is used for daily variations. However, this type of storage only operates under low pressure. Steel gas holders are possible for higher pressures. Bärnthaler et al. [8] discussed and evaluated several options. Empty caverns are used for large quantities [29]. These are not suitable on farm-scale, and thus not considered in our study.

The costs of gas storage must be added to the cost price of green gas as shown in Figure 4.5. The used possibilities for storage are shown in Table 4.3 and are mainly based on Bärnthaler et al. [8]. The investment costs are based on prices of pipes per meter which are suitable for the given pressure.

Storage capacity Q (Nm^3)	Storage type	Investment costs (€)
Q ≤ 10 000	Pipe (8.5 bar, no extra compression needed after upgrading)	222*Q
10 000 < Q ≤ 300 000	Pipes (100 bar, extra compression needed)	2 240 000 + 18.85*Q

Table 4.3: Gas storage: Capacity (Q), type and investment costs.

At a storage capacity lower than 10 000 Nm^3 an 8.5 bar pipe is cheaper, above 10 000 Nm^3, a 100 bar pipe including compression is cheaper. This was implemented in the model. Storage capacity larger than 300 000 Nm^3 is not considered to be useful because of spatial limitations. These limitations also prohibit the use of very low pressure storage techniques.

Scenario 3 – Adding an extra digester

In this scenario it is assumed that the yearly gas demand is met by two digesters, both generating a constant biogas output. Referring to Figure 4.3, digester 1 continuously produces the minimum gas demand. Digester 2 is defined such that it produces the rest of the yearly gas demand, but always in 6 months (roughly from October till March). I.e., if e.g. digester 2 produces 800 000 Nm^3 annually, then the average production is 100 Nm^3/h, but it has to be designed for 200 Nm^3/h. The startup of a second digester might take two weeks when the digester is filled with the effluent (digestate) of another digester [9]. However, startup conditions of this digester are not taken into account, neither a gas demand following capacity. Although both aspects violate reality, these limitations were accepted, because the calculations were merely meant to get an understanding of the possibilities in an economic way. The only extra limitation is that we more or less arbitrarily assumed that in this scenario it is only possible to reach a maximum swing factor SSF=7. A larger SSF would give too large a discrepancy between the constant gas production of both digesters and the actual demand profile. It is assumed that the biogas of both digesters is lead to one upgrading and injection installation, which has to be designed for the maximum hourly production. E.g., if digester 1 is designed for 200 Nm^3/h and digester 2 for 90 Nm^3/h, then the capacity of the upgrading installation must be 290 Nm^3/h.

Sub question 3 – Optimal locations of digesters meeting sustainability criteria

The model as described by Bekkering et al. [12] is taken as a reference. In this study sustainability, also in relation to biomass logistics, was described. Some parameters were implicitly incorporated in the model, others can be calculated and assessed. By analyzing cases where mainly households are involved and mainly companies, we get some insight not only in the type of gas demand, but also in to which extent a supply chain is able to cope with this gas demand. So the results concerning cost price, logistics and sustainability implicitly give indications for optimal locations for digesters and other installations.

4.3 RESULTS

Scenario 1 – Flexible gas production chain

The cost price of green gas as a function of SSF is shown in Figure 4.6 for all considered scales.

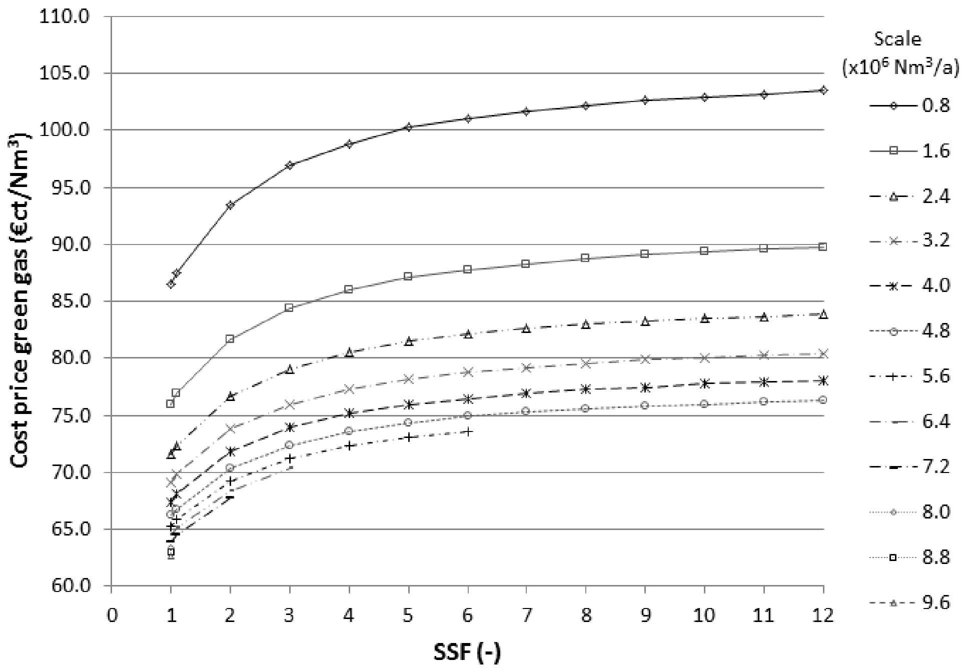

Figure 4.6: Effect of scale and SSF on cost price of green gas (scenario 1).

The cost prices at SSF=1 are by definition those at constant production, and are equal to the (total) cost prices as a function of scale as shown in Figure 4.5. At increasing scale, the difference between minimum (SSF=1) and maximum (SSF=12) cost price decreases, i.e. the cost of flexibility is decreasing at increasing scale. At scale 9.6x10^6 Nm^3/a, no demand following capacity is possible because at SSF=1 the maximum production of capacity 1200 Nm^3/h is reached. This also explains why the lines for scale 5.6x10^6 to 8.8x10^6 are not drawn for all SSF's.

Scenario 2 – Constant gas production with gas storage

The cost price of green gas as a function of SSF is shown in Figure 4.7 for three scales. The shown values represent the cases where storage is possible within the given limits, i.e. for all other cases a storage capacity of more than 300 000 Nm^3 would be needed.

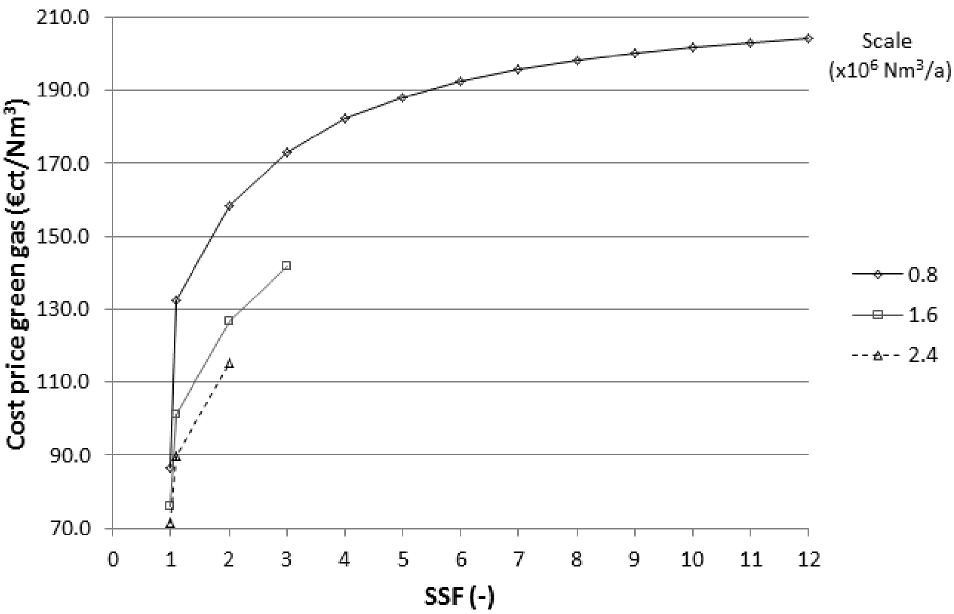

Figure 4.7: Effect of scale and SSF on cost price of green gas (scenario 2).

The large difference in cost price between SSF=1 and SSF=2 is because at SSF=1 no extra storage is needed at all.

Scenario 3 – Adding an extra digester

The cost price of green gas as a function of SSF is shown in Figure 4.8 for all scales. No cost prices were calculated when the design capacity of a digester (obviously always digester 2) would exceed 1200 Nm^3/h. This is the case for scales $7.2x10^6$ Nm^3/a and larger. E.g., this means that for scale $9.6x10^6$ Nm^3/a only an SSF=2 is achievable in terms of gas demand following capacity. Also in this scenario, the much lower cost price at SSF=1 than at SSF=2 is because at SSF=1, no extra digester is needed. As in scenario 1, the difference between minimum (SSF=1) and maximum (SSF=12) cost price decreases at increasing scale.

For all scales a comparison can be made between the three scenarios. For scales $0.8x10^6$ Nm^3/a and $2.4x10^6$ Nm^3/a this is presented in Figures 4.9 and 4.10. The latter may be considered to be a more or less average farm-scale gas supply chain.

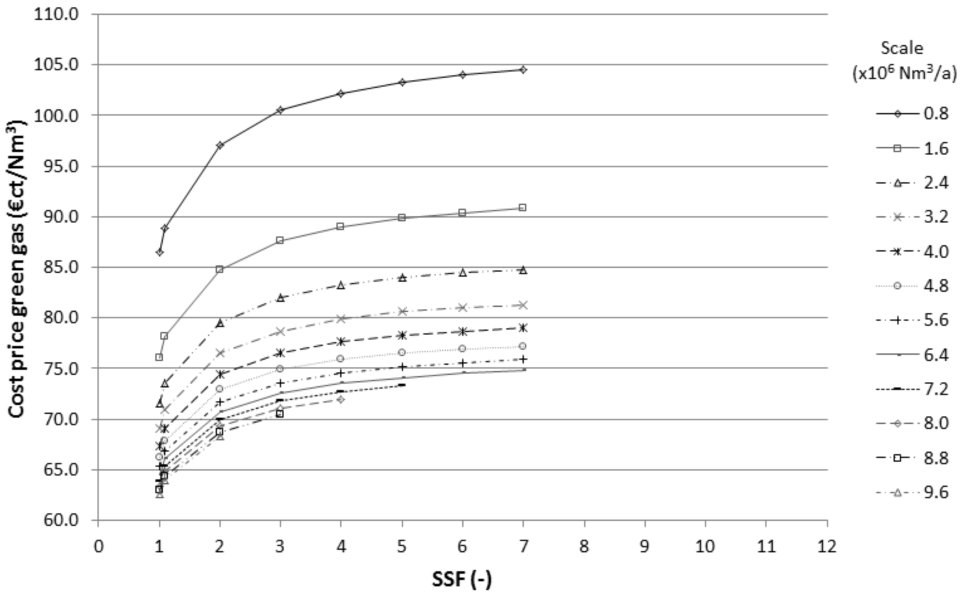

Figure 4.8: Effect of scale and SSF on cost price of green gas (scenario 3).

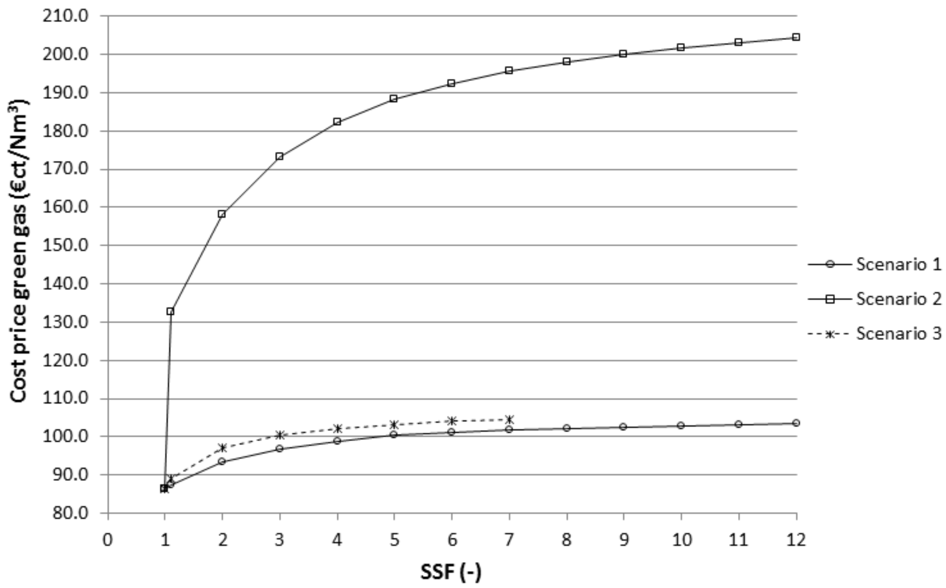

Figure 4.9: Cost price of green gas as a function of SSF for all three scenarios, scale 0.8x10^6 Nm^3/a.

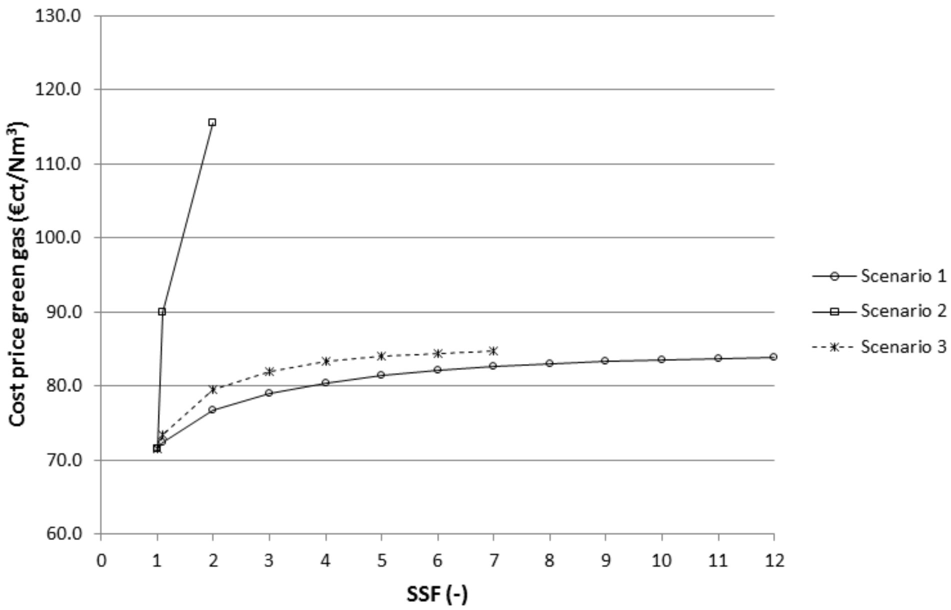

Figure 4.10: Cost price of green gas as a function of SSF for all three scenarios, scale 2.4x10^6 Nm^3/a.

It is evident that gas storage (scenario 2) is not only the most expensive option, but is also not suitable for most SSF's.

4.4 DISCUSSION

The results suggest that adding an extra digester gives more realistic possibilities for flexibilisation than gas storage. Storage is in all cases the most expensive option, and has large spatial disadvantages at increasing SSF and increasing scale. Furthermore, from a supply chain point of view, flexible biogas production is the cheapest option. In our research we assumed that this is technologically possible, although it will need further research to which SSF this is achievable. It is evident that one has to pay for flexibility. Note again that gas storage in the gas grid is not considered in our study.

In general, with the preconditions in our research, the possibilities for flexibilisation decrease at increasing scale. At scale 0.8x10^6 Nm^3/a results could be calculated for all scenarios. At scale 4.8x10^6 Nm^3/a only flexible production and adding an extra digester are possible, at larger scales not for all SSF's. At scale 9.6x10^6 Nm^3/a only a maximum of SSF=2 can be achieved, by adding an extra digester. In order to achieve flexibility at such large scale, central gas storage would be needed, e.g. in empty caverns or gas fields. This would thwart a decentralized energy supply to customers, because gas could only be stored at very specific locations at high investment costs and large amounts. But also in our model the investment costs for two digesters and upgrading plant at higher scales are several millions of euros. High investment costs for famers might be limiting in possibilities as well.

In Schouten et al. [7], options for storage volume reduction were investigated: variable production, two plants instead of one, reducing the percentage of hydrogen to be injected during certain time intervals a year. A significant volume reduction of storage was shown to be possible, although cost price effects were not considered. In our study, a combination of scenario's 2 and 3 would have similarities to Schouten et al. [7], but it seems that adding extra installations to a green gas supply chain would increase the cost price even more.

In this research, we investigated a policy where natural gas is to be replaced by green gas in a given geographical region. Another approach could be that green gas is injected into the gas grid when the gas price is high. Then storage would be needed anyway.

The question arises if an upgrading plant can be used only in summer. Gas demand in winter is much higher, which might mean that biogas does not have to be upgraded.

Concerning sub question 3, Bekkering et al. [12] found that, under assumptions, scale should not very much exceed 250 Nm^3/h from a sustainability point of view.

A comparison between options at a given cost price can be made as well. Referring to Figure 4.6, it is interesting to see that at for instance at a cost price 76 €ct/Nm^3 one might choose a scale $1.6x10^6$ Nm^3/a with SSF=1 as well as a scale $3.2x10^6$ Nm^3/a with SSF=3 or $4.8x10^6$ Nm^3/a with SSF=10. The same effect can be seen for scenario 3. In some cases, to optimize cost price of green gas, it is more interesting to increase gas demand following capacity than to only increase production capacity. Under circumstances, this might also give opportunities to increase the number of relatively small digesters instead of building one big one. This enhances security of supply.

4.5 CONCLUSIONS

Modeling a seasonal gas demand, based on measured demand data, can be done by a sine function under plausible assumptions. This holds for all considered gas demand patterns, and range from household type of consumers as well as large companies. Very specific type of users, such as a bakery or a laundry [8], have not been analyzed.

Three scenarios for flexibilisation of a green gas supply chain were identified and analyzed: Flexible biogas production, constant biogas production combined with gas storage, and two biogas plants with a constant biogas output, of which one is operated only during several months a year. Comparing the cost price results of the three analyzed scenarios, it is evident that gas storage is more expensive than flexible production or adding an extra digester. Flexible biogas production is the cheapest. This holds for all SSF's. However, no relevant literature could be found on research concerning actively steering the output quantity of digesters in time. In this respect, there seem to be possibilities to a certain extent, but these are more indicated by practical experience than by sound scientific knowledge. This means that, with the current knowledge, the stability of the digestion process is not guaranteed at flexibilisation. Therefore, based on the current state of technology, green gas supply chains which meet a gas demand with a relatively low SSF will be more successful than when a high SSF needs to be met. This means that production plants should preferably be located near industrial areas.

At increasing scales, the possibilities for flexibilisation in the supply chain decrease. Limitations for scaling up are the chosen maximum values for gas storage capacity and a maximum production rate of a digester. At the largest considered scale (1200 Nm^3/h green gas), only an SSF=2 is achievable by adding a second digester. For increasing flexibility of the supply chain further, very large gas storage facilities would be needed.

4.6 FURTHER RESEARCH

Further research into a flexible green gas supply chain is interesting, not only in terms of potential cost savings, but also in terms of increasing the possibilities of natural gas replacement on a decentralized level.

It is interesting to investigate the possibilities of several crops a year, e.g. maize, grass, or leftovers, where the crops are fed to the digester. This might reduce the need of co-substrate storage and cost price of green gas. The calculations in this research have been done under the assumption of varying load in digester by amount, not different types of co-substrate. Further research is needed for steering biogas production of digesters.

There are some possibilities for seasonal variation in biogas production. However, to which extent and the consequences for process stability need further research.

Consequences for other types of demand curves need further research.

The feasibility of putting demand following capacity in practice will depend on policy and regulations. The desirable scale of storage is part of this discussion. Storage in the existing grid might be done at very low costs, but is not considered in our model. A research question could be how the grid should be dimensioned, not only to supply enough gas (Nm^3/h), but also to balance supply and demand [30]. Recently, research into gas storage technologies and more specific in gas hydrates has started in The Netherlands (EDGaR). It would be interesting to consider the effects in our model in a later stage.

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5

DESIGNING A GREEN GAS SUPPLY TO MEET REGIONAL SEASONAL DEMAND – AN OPERATIONS RESEARCH CASE STUDY

This chapter is submitted to Applied Energy (June 2014) as:
Bekkering J, Hengeveld EJ, Gemert WJTh van, Broekhuis AA. Designing a green gas supply to meet regional seasonal demand – An operations research case study.

Abstract
One of the issues concerning the replacement of natural gas by green gas is the seasonal pattern of the gas demand. When constant production is assumed, this may limit the injected quantity of green gas into a gas grid to the level of the minimum gas demand in summer. A procedure was proposed to increase the gas demand coverage in a geographical region, i.e. the extent to which natural gas demand can be replaced by green gas. This was done by modeling flexibility into farm-scale green gas supply chains. The procedure comprises two steps. In the first step, the types and number of green gas

production units are determined, based on a desired gas demand coverage. The production types comprise time-varying biogas production, non-continuous biogas production (only in winter periods with each digester having a specified production time) and constant production including seasonal gas storage. In the second step locations of production units and injection stations are calculated, using mixed integer linear programming with cost price minimization being the objective. Five scenarios were defined with increasing gas demand coverage, representing a possible future development in natural gas replacement. The results show that production locations differ for each scenario, but are connected to a selection of injection stations, at least in the considered geographical region under the assumed preconditions. The cost price is mainly determined by the type of digesters needed. Increasing gas demand coverage does not necessarily mean a much higher cost price.

5.1 INTRODUCTION

Several studies assess bioenergy potential and costs on a global, continental or national level. Relatively few describe the spatial distribution of bioenergy production potential and the costs of bioenergy supply within a defined small geographical region [1], although the number of studies in this field is increasing (e.g. [2],[3]). The benefits of gaining quantitative knowledge of possible plant locations, plant scales and logistics to decrease costs were discussed previously ([4],[5]). Research in the field of local or regional energy supply gives a better understanding of the implications of a national or more global energy policy. E.g., the benefits and costs of increasing levels of regional energy self-sufficiency were investigated ([6],[7]). Three closely related principles in this respect are the use of renewable energy resources within a region rather than energy imports, decentralization of the energy system (from national to regional), and increase in the energy efficiency of the supply and the demand side.

Published studies on facility location problems give insight in possible modeling approaches and relevant preconditions depending on the area considered, and the results show where to build facilities. A number of studies exist in which geographical locations of bioenergy plants are calculated for larger regions or countries, under specified boundary conditions, e.g. power plants and factories in a Spanish region [8], or ethanol refineries in Sweden [9]. Some studies take yearly changes in demand or demographic developments into account, (e.g. [10],[11]), but studies predominantly consider supply and demand in a more or less static way. I.e., the long-term supply of biomass and demand for bioenergy are considered constant in time. Usually, seasonal differences between supply and demand are not addressed. Moreover, published studies mainly comprise production of electricity or fuels like ethanol or methanol.

In this paper we focus on bioenergy in the form of green gas, with the aim to calculate biogas plant locations in a sub-municipality scale rural region in The Netherlands. Possibilities for green gas production are strongly dependent on the geographical region considered. A simple, local green gas supply chain may consist of co-digestion of one co-substrate type with available dairy cattle manure, upgrading the produced biogas to natural gas quality and injection into the natural gas grid. Such a supply chain may represent the activities of one farmer, and was earlier investigated [12]. The costs of such a supply chain can be calculated by summing the costs of each process step. Even when cost functions are not linear or non-continuous, because of differing technologies or scale-dependent cost functions, the costs per Nm^3 green gas can be determined. The cost price calculation is slightly expanded when two or more injection stations to choose from are present in the same geographical region. A network of more digesters and injection stations rapidly increases the number of possibilities of plant locations and connections, and thus the number of calculations for an optimization.

Meeting a varying seasonal gas demand was investigated in a study where the gas demand in a region was modeled by a sine function [13]. A seasonal swing factor (SSF) was defined, being the maximum hourly gas demand divided by the minimum hourly gas demand in one year, based on this sine function. An SSF = 1 means a constant gas demand during a year. The higher the SSF, the greater the challenge to match demand and supply. In the mentioned study SSF's ranging from 1.2 to over 20 were found, depending on consumer type. If a geographical region is considered with a known hourly gas demand, SSF = 1, and a known natural gas grid, then the green gas might be relatively cheap if large scale plants are possible, provided that there are no limitations on available biomass or grid entry capacities. Optimal plant locations can then be calculated resulting in a minimum cost price. At larger SSF, e.g. SSF = 12, the minimum hourly gas demand may be relatively low. If constant gas production is assumed without storage, large scale plants may not be possible, implying cost price increase. Up to date, the minimum hourly gas demand is, in combination with a constant supply, considered to be a limiting factor for replacement of natural gas by green gas (e.g.[14],[15]). The question arises whether the choice of the locations in a given region is influenced by the extent to which a supply chain has to cope with a given SSF, i.e. the extent to which the gas demand has to be covered by green gas. The above considerations justify a more in-depth geographical analysis of promising locations to build green gas supply chains. I.e., given a known, time-varying gas demand in a geographical region, how can optimal production locations and

connections between production locations and injection stations be determined? The central research question considered in this study is therefore:
Given a geographical region with a known seasonal gas demand (and thus SSF), and possible geographical locations for production plants and gas injection stations, which combination of locations gives the lowest cost price when defined shares of the gas demand, i.e. gas demand coverage (GDC, up to 100 %), have to be met by green gas?

Sub questions to be answered are:

1. How can feasible geographical locations and capacities of green gas production units and gas entry points be defined in this region?
2. How to model a flexible green gas supply chain? Flexible means that the green gas output of the chain can be varied in time to meet seasonal differences in gas demand. More specific, based on Bekkering et al. [13], which choices must be made between flexible biogas production, gas storage and multiple digesters?

The research is novel in the sense that not only biogas plant and injection station locations in a defined geographical region are calculated in a case study under the condition of (partially) following the seasonal gas demand, but that also the sensitivity of these locations to increase in natural gas replacement is investigated. The intention of answering the research question is to gain a better understanding of possible developments in locally or regionally matching supply and demand. And more specifically, insight is gained in whether requirements on the GDC, which may be a political decision, would influence investment decisions.
To the authors' knowledge no literature exists which defines at which geographical scale energy supply should be considered. E.g., Meyer et al. [2] and Burgess et al. [3] chose a geographical area for their calculations, but no explanation was given what this choice was based on. It is not clear how large such a geographical region should be, although political divisions might be determinative [7]. Investigations for green gas injection have been done for a selected region in the north of The Netherlands [16]. The potential of manure in this region was investigated, but not specified per farm. In this region, theoretically the available manure, together with co-substrates, would be sufficient to meet the gas demand of this region. We chose part of this region for our study.

Literature was reviewed concerning promising modeling approaches for our study. Concerning models, a basic distinction can be made between top-down optimization models (often linear programming, LP) and bottom-up agent based simulations (ABS). Optimization models are useful for finding optimal configurations for one or multiple objectives. Optimization models provide information about the optimal network configurations but do not provide insights into how these network configurations can be achieved. ABS is useful to study system behavior as a function of the interaction of agents and their dynamic environment. Or, ABS provides insights into the consequences of different policy instruments on the evolution of a network, but do not, by nature, provide a framework for comparing the value of these consequences ([17],[18],[19]). ABS is particularly useful when complex interactions between system entities exist, such as autonomous decision making or negotiation. E.g., a possible spatial diffusion of agricultural biogas plants in two German states was modeled for a time span of 2008 to 2028 [20]. In this research a GIS based ABS was used to calculate yearly investments. Based on available biomass in districts and municipalities, it was assumed that biogas was used to produce electricity. For the surplus heat several options were considered based on the known heat demand.

Optimization models, i.e. continuous location models, network location models, mixed-integer programming models and their applications have been reviewed extensively [21]. Previous work on simulation and optimization models concerning agri-chains was analyzed ([22],[23],[24],[25]). Velazquez et al. presented a calculation model to determine locations for power plants based on energy demand of cities in a geographical region [8]. They recognized that the same could be done on the basis of available biomass in the same region, but did not investigate this in their study. Kocoloski et al. chose an MILP approach in their study [4]. The capital costs as a function of capacity were linearized and were defended by stating that a linear approximation fits a decreasing scale factor for higher capacities. This phenomenon was also discussed before [26], but leaves the stronger non-linearity at smaller scales unresolved, while smaller scales may be preferred from a sustainability point of view. Kim et al. addressed the problem of uncertainty of data (e.g. supply amounts, market demands, market prices) in their MILP model for the optimal design of biomass supply chains [27].
Hiremath et al. make a distinction between LP with which a single goal is optimized (e.g. costs) and goal programming (GP) with multiple goals, which may be overachieved or underachieved [28]. The objective is then to minimize the deviations from these goals. A multi-objective optimization model was used to investigate trade-offs between energy cost and environmental impact [29]. Because of the differences in modeling approaches, another study compared a hybrid method to a stochastic and an exact optimization method [30]. In their facility location study, Kocoloski et al. compared the results of their MILP model to three other algorithms: 1) sequential facility siting algorithm, 2) a clustering algorithm and 3) uninformed facility placement, where facilities are placed randomly at

potential facility locations [4]. They found that alternative 1, where facilities are placed one at a time, choosing the location that minimizes the cost for each facility individually, given the distribution of biomass supplies and the locations of previously placed plants, performed well compared to the MILP model. The MILP model showed the lowest cost price for larger scales, but was more or less equal to alternative 1 for smaller scales.

Usually the optimization approaches do not take time aspects into account, e.g. what might happen with energy demand after some years [31]. However, some studies are available which consider time or development aspects. Possible locations of gasification plants in Austria were studied, based on three scenarios, each resembling a different gasoline replacement by methanol [32]. The number of plants increased with increasing methanol demand, but one location stayed the same for each scenario. Leduc et al. formulated a mixed integer program to calculate locations for biomass based methanol production plants [10]. Time aspects were considered by implementing future trends in demography and fuel consumption in scenarios as well as different scales of the production plant.

A different approach was chosen by Weidenaar [33]. From a distribution system operator (DSO) perspective, possible locations for biogas production, and upgrading and injection into the gas grid were explored, based on two performance criteria: CO_2 emission reduction and costs. This was done by assigning probabilities to biomass allocations, digester and upgrading locations, and injection options. For each configuration based on these probabilities the outcomes were calculated, which gave insight in possible pathways.

Considering the studied literature, optimization studies mainly comprise linearized problems. It is merely the bioenergy types and incentives or preconditions which are studied. In our study, the goal is to meet a gas demand at lowest cost. To achieve this, the problem is considered as an optimization problem. Preselecting appropriate facility scales gives opportunities to linearize the problem. Therefore, in our study an MILP approach was chosen. The approach to answering the research questions is discussed in the following section. In section 5.3 the results of our analysis are presented and in section 5.4 we discuss the results, after which the conclusions are presented in section 5.5.

5.2 METHOD

In this case study the region was chosen such that the gas supply to the users (residences and industrial areas) in this region is from one Gas Receiving Station (GRS), see Figure 5.1. Therefore the hourly gas demand of this relatively isolated region is known. The gas demand data and geographical locations of optional green gas entry points of the selected region were received from Rendo, a Dutch Distribution System Operator (DSO).

Figure 5.1: Map of the distribution grid with selected possible locations of production units on farms (F) and injection stations (I). The black lines depict the 8 bar gas grid. The chosen area is some 8.5 x 5 km (4250 ha). Injection station I1 is the current GRS. Coordinates of farms and injection stations can be found in appendix 1.

The end users are mainly residences, resulting in a high SSF. The agricultural area gives possibilities for producing biogas and injecting the upgraded biogas into this gas grid. For the chosen region, the total gas demand in one year was almost 8 600 000 Nm^3, the hourly gas demand is shown in Figure 5.2.

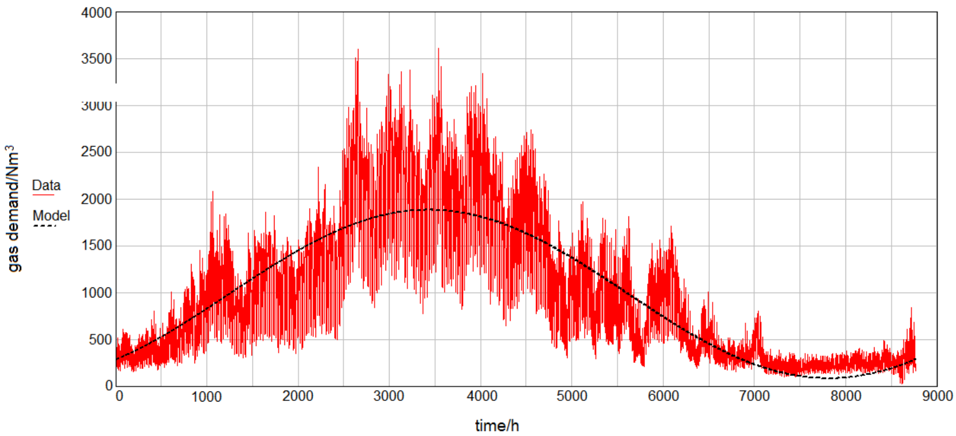

Figure 5.2: The annual gas demand of the specified region (measured data of 8760 hours) and the measured data modeled by a sine function. Properties of the measured data: average 981 Nm^3/h, max. 3610 Nm^3/h, min. 26 Nm^3/h. Properties of the sine function: average 981 Nm^3/h, max. 1888 Nm^3/h, min. 81 Nm^3/h, SSF = 1888/81 = 23. The total gas demand in one year was 8 589 842 Nm^3 [13].

When 8000 production hours are assumed (based on [34]), this would correspond to an average green gas production of 1075 Nm^3/h, or 1825 Nm^3/h biogas (co-digestion dairy cattle manure and maize). Theoretically, a (very) large digester would be able to produce this amount when constant production is assumed, not taking seasonal aspects into account. Till now such digesters have not been built in The Netherlands. Usually the green gas production capacity on farms and injection into the gas grid is around 200 Nm^3/h per farm [35]. Increasing scale implies decreasing cost price of the green gas, but also slightly decreasing energy efficiency and greenhouse gas reduction and increasing biomass transport movements. In the present study we considered an average (in a year) green gas production capacity of 300 Nm^3/h to be a maximum scale from a sustainability point of view. This is based on a desired maximum number of transport movements for the transport of manure, co-substrates and digestate. The number of transport movements to and from one farm evidently increases with increasing scale of the facility at that farm.

Sub question 1 – Locations of green gas production units and entry stations

Green gas production units are the combination of manure transport, co-substrate production and transport, and biogas and upgrading plants, which are considered to be located at farms. At the considered scales, this seems to be preferable from a spatial and social acceptance perspective [36]. Within the chosen region, five farms were identified as possible locations for digesters and upgrading installations. Farms close to a village were considered not to be feasible for social acceptance reasons. Multiple digesters may be placed on a farm, but the (assumed) maximum capacity per location cannot be exceeded. Possible locations for green gas injection stations were provided by Rendo. Existing locations where the pressure in the grid is reduced from 8 bar to 300 mbar and where a substantial gas demand is measured (maximum demand hundreds Nm^3/h) were chosen as injection stations. The maximum capacities of the injection stations are chosen equal to this maximum measured gas demand, which ensures that the current gas grid capacity suffices everywhere. Detailed grid flow calculation may be needed when other locations or capacities of the distribution grid would be chosen. It was checked that the total capacities of farms and injection stations were sufficient to meet the total annual gas demand in the area. See Figure 5.1 and Appendix A for the properties of the locations of production units (farms) and injection stations.

Sub question 2 – Modeling time-varying green gas supply chains

In order to make the desired calculations, the green gas supply chain as described in [12] was adapted, see Figure 5.3.

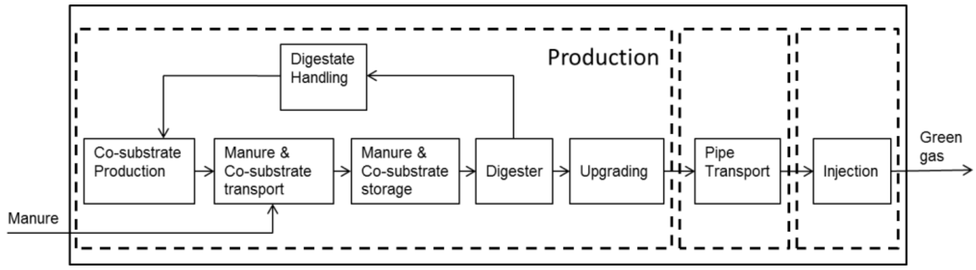

Figure 5.3: A green gas supply chain covered in three parts (dashed boxes): Production (from co-substrate production to upgrading the biogas on farms), Pipe Transport (of upgraded biogas) and Injection into the gas grid.

The transformation blocks Co-substrate Production till Upgrading are put in one container block called Production, subject to the following assumptions and preconditions:

- Collecting manure and co-substrates is thought to take place in a circular area with the farm in the center of this circle, based on [12].
- Co-digestion of cow manure and maize is considered, the mass fraction of maize is 50 %.
- Biogas and upgrading plants are to be located on farms. The biogas produced on a farm is upgraded to green gas on the same farm, so no biogas grid is assumed.

Furthermore, transformation blocks Pipe Transport and Injection are used. The block types Production and Injection each have a green gas cost price as a function of scale and SSF, e.g. see Figure 5.4 when SSF = 1.1. The costs of predefined scales are entered into the model. Costs of Pipe Transport are considered to be scale independent and only a function of length: 0.0015 €ct/(Nm^3·m), based on calculations in [37].

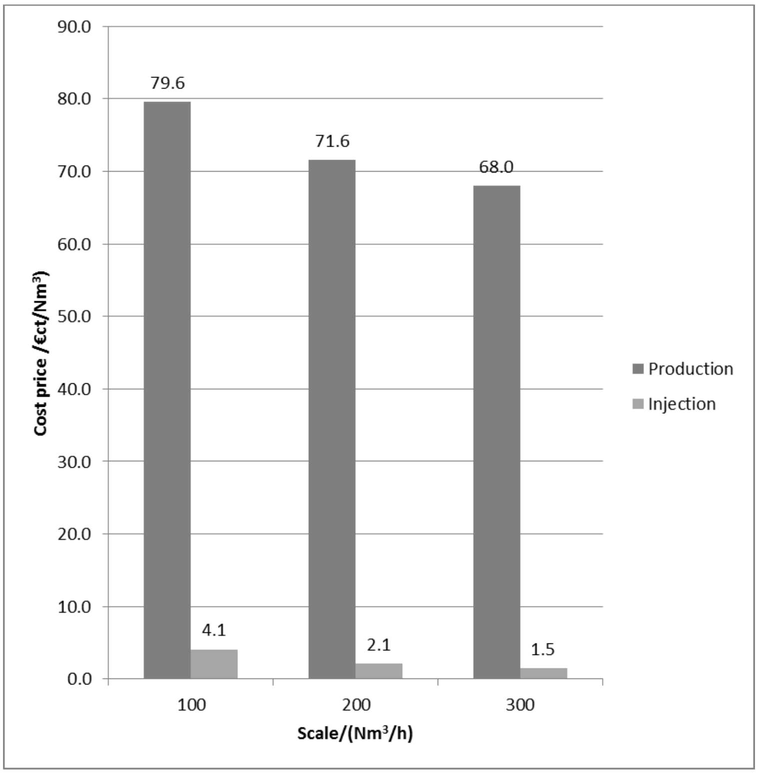

Figure 5.4: Cost price (at SSF = 1.1) for Production and Injection at scales 100 Nm^3/h to 300 Nm^3/h. 300 Nm^3/h is considered to be the maximum scale from a sustainability point of view.

The green gas injected has to meet the gas demand to a specified extent, expressed by the GDC (gas demand coverage). The gas demand is modeled by the first order sine function using Fourier transformation [13], see Figure 5.2 again for the considered situation. Mathematically the GDC is defined by the share of the area under the sine curve of Figure 5.2 which is delivered by green gas. For convenience reasons, the annual gas demand was taken to be 8.0 × 10^6 Nm^3/a with SSF = 20, close to the measured data. For only meeting the minimum gas demand, a constant production equal to the minimum of the sine would then be 95 Nm^3/hr. This corresponds to GDC = 9.5 %, see Appendix B. Achieving a higher

GDC can be done in several ways, possibilities were explored before in three scenarios [13]:

1. digesters with time-varying biogas production/upgrading, in the present study referred to as flexible production (fp).
2. periodically turning on (winter) and off (summer) an extra digester, having a constant output rate during operation. In this study this is referred to as winter production (wp).
3. digesters with a constant production rate with green gas storage under high pressure, in this study referred to as production with storage (cs).

One of the conclusions was that flexible biogas production would be the most promising in terms of cost price. Constant production with gas storage is by far the most expensive. As an example, see Figure 5.5 for an impression how the gas demand can be partly met by flexible production and winter production (corresponding to scenario 3, as described hereafter).

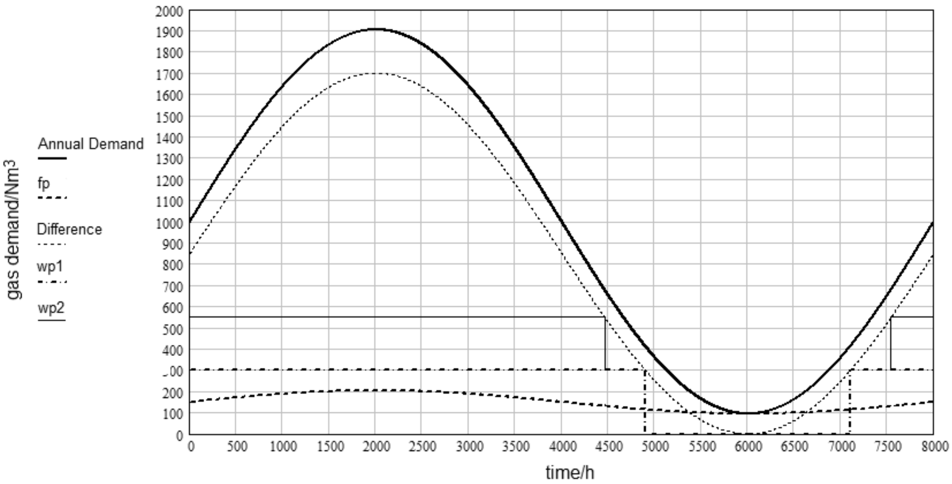

Figure 5.5: Example of partially meeting an annual gas demand. The Difference between Annual Demand and fp (flexible production, with SSF = 2.15) is shown. This can be met by winter production (wp) and/or production with storage. Here two winter production units are shown, with capacity 300 Nm^3/h (wp1) and 250 Nm^3/h (wp2) respectively. These two production units have different production periods per annum. Actually, the GDC is defined by the share of the surface under the annual demand curve which is covered by green gas production.

5 scenarios with GDC's 10 %, 20 %, 50 %, 80 % and 100 % were analyzed in the present study. The increasing GDC's in the successive scenarios depict a possible development in

time of replacing natural gas by green gas. The chosen strategy to achieve a higher GDC is by implementation of flexible production, winter production and production with storage, in the mentioned sequence. Temporary overproduction and burning of excess gas is not taken into consideration. The scenarios, resulting from this strategy, are described below and an overview is given in Table 5.1.

Scenario	GDC	Annual natural gas replacement (Nm^3/a)	Technology
1	10 %	800 000	Flexible production (SSF = 1.1*).
2	20 %	1 600 000	Flexible production with SSF = 2.15, which would produce 1.2×10^6 Nm^3/a, corresponding to GDC = 15 %. The difference between 15 % and 20 % is provided by 1 winter production unit with capacity 100 Nm^3/h, producing for 4000 h.**
2a	23.3 %	1 864 000	Flexible production with SSF = 2.15, which would produce 1.2×10^6 Nm^3/a, corresponding to GDC = 15 %. The difference between 15 % and 23.3 % is provided by 1 winter production unit with capacity 100 Nm^3/h, producing 6640 h.
3	50 %	4 000 000	Flexible production with SSF = 2.15 (producing 1.2×10^6 Nm^3/a). 2 winter production units with capacities 300 Nm^3/h (5787 production hours) and 250 Nm^3/h (4256 production hours), together producing 2.8×10^6 Nm^3/a.
4	80 %	6 400 000	Flexible production with SSF = 2.15 (producing 1.2×10^6 Nm^3/a). 4 winter production units, each having capacity 300 Nm^3/h but different production periods (together producing 5.2×10^6 Nm^3/a).
5	100 %	8 000 000	Flexible production with SSF = 2.15 (1.2×10^6 Nm^3/a), 7 winter production units with capacities 200 Nm^3/h, all having different production periods (with a total production of 5.84×10^6 Nm^3/a), 1 constant production unit with gas storage (0.96×10^6 Nm^3/a). A storage capacity of 200 379 Nm^3 green gas is needed.

Table 5.1: Description of the analyzed scenarios. A production capacity 100 Nm^3/h and 4000 production hours means that the plant is designed for a maximum production of 100 Nm^3/h, the average annual production is 50 Nm^3/h, because of 4000 instead of 8000 production hours.

* *A desired SSF = 1 would mean GDC = 9.5 %, see appendix B.*

** *To meet a GDC = 20 % with flexible production only, an SSF = 3.2 of such production units would be needed, which is considered to be too high.*

The possibilities of flexible biogas production, modeled by a sine function, are limited and need more research ([13],[38]). In the present study we assumed that flexible production is possible to a certain extent, i.e. a maximum achievable GDC of 15 % by flexible production was taken. With a minimum gas demand of 95 Nm^3/h, the corresponding SSF is 2.15, which seems achievable with the current state of technology. This assumption makes that scenario 1 (GDC = 10 %) can be entirely met by flexible production. To increase the GDC further, we chose to add winter production units which are switched off during several months (in the summer season). The annual quantity to be produced determines the optimal combination of design capacity (Nm^3/h) and production time (hours) of winter production units from a cost price point of view. For scenario 2 (GDC = 20 %), the total production is done by one flexible and one winter production unit. The winter production unit has a design capacity 100 Nm^3/h and produces during 4000 h/a in order to reach the desired GDC. But the unit could produce for a longer period before production exceeds the difference between annual demand and flexible production, actually 6640 h/a. Therefore, scenario 2a was added to investigate this effect, and results in GDC = 23.3 %. The GDC's of scenarios 3 (50 %) and 4 (80 %) can also be reached by adding winter production units. For a further increase in GDC up to 100 % (scenario 5), a unit with constant production and green gas storage are needed. Storage is done in large pipes under high pressure. Calculations showed that storage is so much more expensive than winter production, that it would be cheapest to build many small scale winter production units (design capacity 100 Nm^3/h) at scenario 5. This keeps the storage need as low as possible. However, in that case many production units would be needed. For practical reasons we chose to use a design capacity of 200 Nm^3/h for scenario 5. Using the existing gas grid as a storage is not considered.

Summarizing:

- From a cost price point of view, flexible production is more preferable than winter production or production with storage.
- If winter production is needed but storage can be avoided, then the cost price of winter production is determined by the design capacity (Nm^3/h) and the corresponding production period (hours). Comparing this cost price for design capacities 100 Nm^3/h, 200 Nm^3/h and 300 Nm^3/h, the minimum determines the design capacity of the winter production units.
- If storage is needed, then the capacity of the winter production units should be chosen as low as possible. As this would lead to many production units, we chose a capacity of 200 Nm^3/h in this situation.

For all scenarios, the procedure comprised two steps. First, for each scenario (with defined GDC), the type and amount of production units were determined. Subsequently, these production units were input of the MILP problem to be solved, i.e. to be allocated to geographical locations. The investment costs were based on the design capacities and the cost price per Nm^3 green gas was based on the average annual production. The objective of the model is a minimum average cost price of the injected green gas (€ct/Nm^3). The mathematical formulations of the MILP problem are presented in Appendix C for each scenario. These expressions were reformulated in the spreadsheet software MS Excel.

5.3 RESULTS

The aim of the study was to gain insight in locations of production units and injection stations and the cost price of the injected green gas for the considered scenarios. For the subsequent scenarios, representing an increasing GDC, Table 5.2 shows the calculated locations of the production units by installation types and scales.

Scenario Farm	1 (GDC = 10 %)	2 (GDC = 20 %)	2a (GDC = 23.3 %)	3 (GDC = 50 %)	4 GDC = 80 %)	5 (GDC = 100 %)
F1	-	-	-	fp150	fp150	wp200 (2x)
F2	-	-	-	wp250	-	wp200
F3	-	-	-	wp300	wp300 (2x)	wp200 (2x)
F4	-	-	fp150	-	- wp300	fp150 wp200
F5	fp100 - -	fp150 wp100 -	- wp100 -	- - -	- wp300 -	- wp200 cs100

Table 5.2: Calculated locations of production units (on farms F1-F5). The geographical positions of the farms can be found in Figure 5.1 and the coordinates in appendix 1. fp = flexible production (SSF > 1), wp = winter production, cs = constant production with storage (production constant during the year). The number behind a letter depicts the average hourly production in the case of flexible production, and depicts the design capacity of a production unit in the case of winter digesters and constant production with storage. A value between brackets depicts the number of production units (of one type and design scale) present on one location when more than one is needed. Note again that, for each scenario, each single winter production unit is unique in its amount of production hours.

Taking scenario 3 as an example, a flexible production unit (fp150) with average production 150 Nm^3/h (in a year) and 8000 production hours per annum is located at farm F1. Two winter production units (wp250 and wp300) are located at farms F2 and F3: wp250 has a design capacity of 250 Nm^3/h and 4256 production hours per annum, and wp300 has a design capacity of 300 Nm^3/h and 5787 production hours per annum.

Table 5.3 shows the calculated locations of the injection stations.

Scenario Injection station	1 (GDC = 10 %)	2 (GDC = 20 %)	2a (GDC = 23.3 %)	3 (GDC = 50 %)	4 (GDC = 80 %)	5 (GDC = 100 %)
I1	-	-	-	F1, F2, F3	F1, F3	F1, F2, F3
I2	-	-	-	-	-	-
I3	-	-	-	-	-	-
I4	F5	F5	F4, F5	-	F4, F5	F4, F5
I5	-	-	-	-	-	-

Table 5.3: Calculated locations of used injection station locations (I1-I5), depicted by the farms to which these stations are connected. The geographical positions can be found in Figure 1 and the coordinates in appendix 1.

Taking scenario 3 as an example again, only injection station I1 is used: Green gas produced at farm F1, F2 and F3 is transported to this injection station by pipelines.

For all scenarios the average cost price of green gas is shown in Figure 5.6.

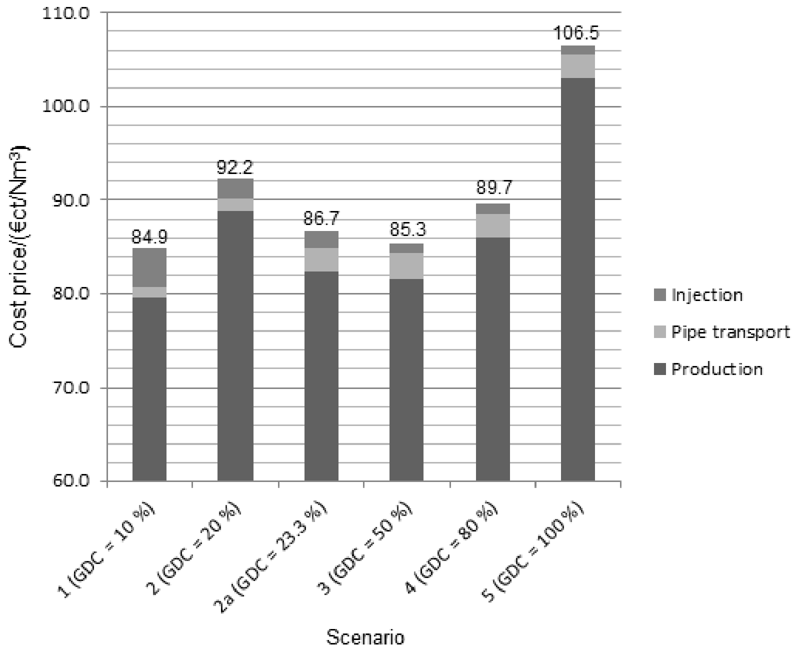

Figure 5.6: Green gas cost price for all scenarios. Note that the cost price of a reference supply chain, with SSF = 1 and a pipe transport distance equal to the distance between F5 and I4, is 83.8 €ct/Nm^3 at scale 100 Nm^3/h, 73.5 €ct/Nm^3 at scale 150 Nm^3/h and 69.2 €ct/Nm^3 at scale 300 Nm^3/h.

For small GDC's (scenarios 1 and 2), obviously the farm with the shortest distance to an injection station is selected. I.e., for scenarios 1 and 2, the calculated location for production is F5, only the scale of the flexible production unit differs and a winter production unit is added in scenario 2. In scenario 2a winter production is at F4 and not F5, because otherwise the scale limit of F5 would be exceeded. Comparing scenario 2a to scenario 2 shows that the increased costs of pipe transport are clearly outweighed by the cost reduction of production. The production cost reduction is caused by the increased number of production hours of scenario 2a. The increased pipe transport costs are evidently caused by the need for another pipe between F4 and I4. In scenario 3 the situation is different: The production units are located at F1, F2 and F3, and production capacities are higher than for scenarios 1, 2 and 2a. In scenario 4 the flexible production is at F1, and farms F3, F4 and F5 have winter production units. Gas from F1 and F3 is injected in I1, and from F4 and F5 in I4. At scenario 5, flexible production is at F4 again, production with storage takes place at F5. All farms have (multiple) winter production units.

Looking into more detail at one of the scenarios again, a breakdown of the production and costs per farm of scenario 3 (GDC = 50 %) is shown in Table 5.4.

Farm	F1	F2	F3	F4	F5	Weighted average
Production type	fp150	wp250	wp300	-	-	n.a.
Average production* (Nm^3/h)	150	133	217	-	-	n.a.
Production cost price (€ct/Nm^3)	80.4	91.0	76.3	-	-	81.5
Connection to injection station	I1	I1	I1	-	-	n.a.
Pipe transport cost price (€ct/Nm^3)	2.5	3.6	2.6	-	-	2.8

*Table 5.4: Breakdown of costs per farm for scenario 3 (GDC = 50 %). *Average production is defined as the annual production divided by 8000 production hours. E.g., for scenario 3, at F3 a winter production unit with design capacity 300 Nm^3/h is located, with an annual production of 1 736 000 Nm^3 and 5787 production hours (at design capacity). Then the average production is 1 736 000/8000 = 217 Nm^3/h.*

The weighted average of these costs combined with the injection costs (= 1.0 €ct/Nm^3) give the total costs as presented in Figure 5.6. Note that in this scenario the winter production at F3 has a lower cost price than the flexible production at F1. The high cost price of scenario 5 (106.5 €ct/Nm^3) is mainly caused by the digester with storage: 174.4 €ct/Nm^3.

5.4 DISCUSSION

Locations of production units and injection stations have been calculated for several scenarios. It is evident that the cheapest way of replacement of small amounts of natural gas (small GDC) by one production unit is to build a digester on a farm where the distance to an injection station is the shortest. In our case study this is farm F5 and injection station I4, see Figure 5.1. For the small region considered in the present study this can easily be verified by hand calculations, which is a validation of the model at the same time.

Although GDC = 100 % at scenario 5, it is very expensive with a cost price of 106.5 €ct/Nm^3. This high cost price is caused by the costs of gas storage. This raises questions on the desirability of such a situation. Instead of storage, a higher gas production rate in combination with seasonal electricity production or gas heat pumps might be more promising alternatives, depending on electricity and heat or cooling demand. These options were not investigated in this study. Theoretically, a GDC = 100 % could also be reached by many (very) small scale production units, each producing in winter but each at different time lengths, but a high cost price because of scale effects and probable spatial restrictions currently limit the possibilities. However, many small scale production units would benefit the supply reliability of a green gas supply system as a whole, but this is currently not financially rewarded.

For scenarios 1 to 4, the differences between cost prices are less than one might possibly expect. These cost prices vary from 84.9 €ct/Nm^3 (scenario 1) to 89.7 €ct/Nm^3 (scenario 4). Scenario 2 (cost price 92.2 €ct/Nm^3) is omitted in this range because it is clearly less favorable than scenario 2a. Increasing GDC does not automatically imply an increasing cost price, e.g. scenario 3 is slightly cheaper than scenario 2a. This is explained by the scale advantages at scenario 3, i.e. the possibility of larger production units producing during a substantial period a year. Thus, if the policy would be to replace natural gas in the way as investigated in this study, it would be beneficial to be ambitious in terms of GDC.

Yet, the cost price is high compared to prices at constant production. E.g., at scenario 3 (GDC = 50 %), the annual production rate is 4.0 × 10^6 Nm^3/a and the cost price is 85.3 €ct/Nm^3. For comparison, the cost price of green gas, injected into the gas grid, at the same scale 4.0 × 10^6 Nm^3/a but at constant production rate, is 65.0 €ct/Nm^3. So the annual production rate is the same, but 20.3 €ct/Nm^3 cheaper. However, it is difficult to compare these values, because the constant production rate does not take seasonal differences in gas demand into account. The difference can be seen as an indicator for the costs of the flexibility in the production chain.

The calculated cost price is a weighted average of all production units, piping and injection stations, as shown in Table 5.4 for scenario 3. The costs between the production units strongly differ, from 76.3 €ct/Nm^3 to 91.0 €ct/Nm^3. At scenarios 4 and 5 these differences are even bigger. Farmers will not individually invest in production units and piping in these scenarios, because of the differences in costs for the farmers. A cooperation between farmers or other forms of sharing costs and benefits would give possibilities.

As the investment costs of an injection station are a fixed value, it is advantageous to use the maximum capacity of a built station as much as possible. For all scenarios this is the case.

A mathematical approach of a facility location problem implicitly has some rigidity which may not always be desirable when the outcomes are translated into what they mean in reality. E.g., scenario 2a has a lower cost price than scenario 2, because of a better capacity use of winter production. As a result of this, the maximum capacity of F5 (200 Nm^3/h) which was reached at scenario 2, is exceeded at scenario 2a (total needed capacity

233 Nm^3/h). Therefore, at scenario 2a the model calculated that production should also take place at F4, with piping between F4 and I4. However, a sound business consideration would probably be to accept a slightly higher maximum capacity at F5, so that less piping would be needed.

We assumed scale independent piping costs, 0.0015 €ct/Nm^3.m. I.e., these costs only depend on the volume transported and the distance. We considered this acceptable for the scales used for production. A consequence of this choice for linearization is that the production of one farm can be divided over several injection stations. Another injection station than the nearest can be chosen, when scale advantages of the other injection station outweigh the higher transport costs. However, theoretically, transporting higher volumes through a pipe decreases the costs per Nm^3, and incorporating this effect in the model would emphasize the decision to transport as much gas through a pipe as possible. Which effect prevails is not clear at this moment, but incorporating scale effects of piping would clearly enlarge the number of variables in the model to a great extent.

At scenarios 2a, 3, 4 and 5, transport costs outweigh the injection costs. These scenarios also support the idea of building a 'hub' where all the produced gas can be injected (under the precondition of decentralized upgrading). E.g., F2 is closer to I2 than I1, but at scenario 3 I2 is not used because at I1 an injection station will be built anyway. This is described in more detail in [37].

In our study, we did not consider a strict maximum allowed number of production units for each farm, although we chose plausible numbers and scales to be installed. In practice, there may be spatial or other limitations on this number. Moreover, in our study a digester and upgrading installation together were considered to be one production unit. It may need further research to see if more digesters, which may be switched off and on, can be connected to one upgrading installation. This is especially the case for e.g. scenario 3, where 'hub behavior' seems to occur. However, limitations on upgrading installations concerning changing flows and switching on/off may limit the flexibility of centralized upgrading, depending on the chosen technology.

5.5 CONCLUSIONS – FURTHER RESEARCH

The considered geographical region could be self-sufficient in terms of gas, the available biomass would be sufficient to produce green gas as a natural gas substitute. Replacement of natural gas by green gas supply chains for a relatively small region can be modeled in a mathematical way. A procedure was proposed to calculate optimal locations of farm-scale production units and injection stations, based on lowest cost price. For each desired GDC was examined first how the GDC is achieved, i.e. the production types and scales were

determined which can meet the desired GDC. After that, the optimal locations were calculated with an MILP model.
Scale dependent cost prices of production and injection were implemented in the model. This was done by choosing discrete scales, each having a different cost price. The advantage of studying a small geographical region is that scale effects can be studied without the complication of cumbersome calculations.
The case study showed that the optimal locations for flexible production are not the same for all scenarios. The cost prices of the distinctive scenarios are in the same order of magnitude, except scenario 5 (GDC = 100 %). Hence, a GDC of 50 % or 80 % could as well be strived for as e.g. 10 % or 20 %. A growth scenario at which natural gas is replaced by green gas step by step in time, is not supported by this study.
The proposed procedure is generic in its approach and could be applied to smaller and larger regions to investigate its effects on locations, cost price and sustainability aspects. Depending on the actual problems in a region, the model can be expanded to a more complete description where biomass locations are decoupled from farms. At a fixed SSF, the influence of limitations on biomass (type and availability) and grid entry capacities on plant locations in a region could be examined.
The optimization done in this research is based on cost price effectiveness. In practice other factors might influence the decision making, e.g. spatial planning, law, opinions on safety or scale factors. The influence of these other factors might be investigated in further research, for instance with the help of the analytical hierarchy process [39]. Hilst et al. [1] focus on the competitive advantage of bioenergy crops in relation to conventional land use in order to increase understanding of where, and on which types of soils, such land use changes might occur. The current land use and soil suitability for traditional and bioenergy crops were mapped using a GIS. Data from such a study might be used to get a more detailed understanding of local possibilities of green gas.

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5.6 APPENDIX A - PROPERTIES OF PRODUCTION PLANTS AND INJECTION STATIONS

The coordinates of the farms in Figure 5.1, and assumed production capacities, are shown in Table 5.5.

Farm	X coordinate (km)	Y coordinate (km)	Assumed maximum (average) green gas production capacity Q_f/(Nm^3/h)
1	-1.38	0.96	300
2	-2.38	-0.04	200
3	1.62	-0.54	300
4	4.92	0.76	300
5	5.62	1.96	200

Table 5.5: Possible locations of production units, with assumed green gas production capacity per farm. Note that multiple production units can be placed on a farm. The assumed green gas production capacity is based on assumed available biomass. The current GRS was taken as the origin (0,0).

The coordinates of the injection stations in Figure 5.1, and corresponding injection capacities, are shown in Table 5.6.

Injection station	X coordinate (km)	Y coordinate (km)	Maximum capacity Q_i/(Nm^3/h)
1 (= GRS)	0	0	4000
2	-1.68	-1.07	700
3	0.19	1.96	200
4	5.40	2.73	800
5	3.41	2.55	400

Table 5.6: Coordinates of possible injection station, relative to the current GRS, with maximum capacities. It is assumed that some fluctuation in gas supply does not cause problems at the injection station.

5.7 APPENDIX B - RELATION BETWEEN *SSF*, AVERAGE AND MINIMUM GAS PRODUCTION

The general form of a time-varying (green) gas demand $f(t)$ can be described with a sine function [13]:

$$f(t) = c_1 + c_2.sin\left(\frac{2\pi t}{8000}\right)$$

where c_1 is the average hourly gas demand (Nm^3/h) and c_2 is the amplitude (Nm^3/h). If the annual gas demand is 8.0×10^6 Nm^3/a with SSF = 20, then c_1 = 1000 Nm^3/h (8000 production hours), and c_2 is:

$$c_2 = c_1.\frac{SSF - 1}{SSF + 1} = c_1.\frac{20 - 1}{20 + 1} = \tfrac{19}{21}.c_1$$

The minimum gas demand, equal to the minimum of the sine, would be:

$$minimum = c_1 - c_2 = 1000.\left(1 - \tfrac{19}{21}\right) \approx 95\ \mathrm{Nm^3/h}$$

Meeting this minimum gas demand with constant production corresponds to GDC = 9.5 %.

5.8 APPENDIX C - MATHEMATICAL FORMULATION OF THE STUDIED SCENARIOS

First, let F be the number of farms where production units could be located. Production units are the combination of manure transport, co-substrate production and transport, and biogas and upgrading plants. Let I be the number of possible injection points. The following sets are defined:

$$\tilde{F} = \{1, \dots, F\}, \tilde{I} = \{1, \dots, I\}$$

In our study $F = 5$ and $I = 5$. Of each eligible farm $f \in \tilde{F}$ and each injection station $i \in \tilde{I}$ the coordinates (Table 5.5 and 5.6) are put into a matrix. $\tilde{F}$ and $\tilde{I}$ are the same for all scenarios.

Further, for each scenario s let p be a production unit type and scale of the set $\tilde{P}_s$:

$$p \in \tilde{P}_s$$

with

$$\tilde{P}_s \subset \{fp150, wp300_{217}, wp250_{133}, \dots, cs120\}$$

where fp, wp and cs resemble a flexible production unit, a winter production unit or a constant production unit with storage respectively. For fp and cs, the number represents the average production (Nm^3/h). For wp, the number and subscript represent the design scale (Nm^3/h) and average production (Nm^3/h) respectively.

And let $\widetilde{K}_i$ be the set of possible capacities of an injection station location i with $k \in \widetilde{K}_i$:

$$\widetilde{K}_i = \{100, 150, \dots, K_i\}$$

Capacity $K_i \in \widetilde{K}_i$ is the maximum possible quantity (Nm^3/h) of green gas which can be injected at location i. K_i may be different for each i, see Table 5.6 again. E.g., at injection location 4, K_4 = 800 Nm^3/h.

The variables used in the study are shown in Table 5.7.

Variable	Explanation	Type
$u_{f,p}$	Indicates if production unit of type p is present on farm f (=1) or not (=0).	Binary
$q_{f,i}$	Amount of green gas delivered from farm f to injection station i (Nm^3/h)	Continuous (non-negative)
$u_{i,k}$	Indicates if an injection station on location i with capacity *k* is in operation (=1) or not (=0).	Binary

Table 5.7: Variables used in the model.

The object function is the average cost price of injected green gas C_{igg} (€ct/Nm^3):

$$Min\ C_{igg}(q,u) = \frac{1}{Q_{tot}} \cdot \left(\sum_{f=1}^{F} \sum_{p \in \tilde{P}_s} C_p . u_{f,p} + \sum_{f=1}^{F} \sum_{i=1}^{I} C_{f,i} . q_{f,i} + \sum_{i=1}^{I} \sum_{k \in \widetilde{K}_i} C_k . u_{i,k} \right)$$

with Q_{tot}/(Nm^3/h) being the amount of green gas (average over a year) replacing natural gas in a defined region, depending on the scenario. E.g., in scenario 1, Q_{tot} = 100 Nm^3/h to meet the GDC = 10 %.

$$C_p = q_p . C_{production}(q_p)$$

The cost price $C_{production}(q_p)$/(€ct/Nm^3) of green gas produced at a production unit, is based on [12], and is a function of the quantity q_p produced at production unit p:

$$C_{production}(q_p) = C_{MN} + C_{CO} + C_{TR}(q_p) + C_{CS} + C_{DG}(q_p) + C_{DH} + C_{UP}(q_p)$$

The form of the equation is equal for all production units, but the definition of the terms may differ depending on the production unit type. The terms belonging to scenario 1 ($\tilde{P}_1 = \{fp100\}$ with SSF = 1.1) are explained and quantified in Table 5.8.

Item	Explanation	Value/Equation (€ct/Nm^3)
C_{MN}	Cost price Manure	-12.6
C_{CO}	Cost price Co-substrate	28.3
$C_{TR}(q_p)$	Cost price Transport (manure, co-substrate, digestate)	$3.7668 \, . \, q_p^{0.1031}$
C_{CS}	Cost price Co-substrate Storage	2.9
$C_{DG}(q_p)$	Cost price Digester	$47.792 \, . \, q_p^{-0.164}$
C_{DH}	Cost price Digestate Handling	8.3
$C_{UP}(q_p)$	Cost price Upgrading	$104.4. \, q_p^{-0.329}$

Table 5.8: Cost prices of the green gas production chain: These are constants or scale dependent equations, where q_p is the amount of green gas produced at production unit p (Nm^3/h). Based on the model as discussed in [12], but with SSF = 1.1.

E.g., for scenario 1 ($\tilde{P}_1 = \{fp100\}$ with SSF = 1.1), the production cost price is shown in Figure 5.4. For this scenario, Q_{tot} is delivered by one digester (as $\tilde{P}_1 = \{fp100\}$), so $q_p = Q_{tot}$ = 100 Nm^3/h, i.e. the cost price is 79.6 €ct/Nm^3. Then $C_p = q_p . C_{production}(q_p) = Q_{tot}$. 79.6 = 7960 €ct/h.

The cost price $C_{f,i}$ (€ct/Nm^3) of green gas pipe transport from farm f to injection station i is a matrix with the distance (m) between f and i multiplied by a fixed piping cost price (0.0015 €/Nm^3.m, based on [37]).

The cost price $C_I(q_i)$ (€ct/Nm^3) of green gas injection into the grid at injection station i is (with q_i being the amount of injected green gas):

$$C_I(q_i) = 168.65.(q_i)^{-0.823}$$

Using this costs function, the coefficients C_k in the object function can then be found from

$C_k = q_i . C_I(q_i)$. E.g., in scenario 1, at $k = 100$, $q_i = Q_{tot}$ = 100 Nm^3/h, the costs are $C_{100} = Q_{tot} . C_I(q_i)$ = 100 . 4.1 = 410 €ct/h.

The object function is subject to the following restrictions:

1.

$$u_{f,p} \in \{0,1\} \qquad f \in \tilde{F}, p \in \tilde{P}_s$$

2.

$$q_{f,i} \geq 0 \qquad f \in \tilde{F}, i \in \tilde{I}$$

3.

$$u_{i,k} \in \{0,1\} \qquad i \in \tilde{I}, k \in \tilde{K}_i$$

4.

There must be exactly one production unit of each type:

$$\sum_{f=1}^{F} u_{f,p} = 1 \qquad \forall\, p \in \tilde{P}_s$$

5.

The gas produced at farm f, must be transported in pipes connected to that farm:

$$\sum_{p \in \tilde{P}_1} q_p \, . u_{f,p} = \sum_{i=1}^{I} q_{f,i} \qquad \forall\, f \in \tilde{F}$$

6.
The gas transported to an injection station i, must be less than or equal to capacity k of this injection station:

$$\sum_{f=1}^{F} q_{f,i} \leq \sum_{k \in \tilde{K}_i} k\,.\,u_{i,k} \qquad\qquad \forall\ i \in \tilde{I}$$

7.
Each farm f has a maximum quantity Q_f/(Nm^3/h) gas that can be produced, based on available manure and co-substrate (from Table 5):

$$\sum_{p \in \tilde{P}_1} q_p . u_{f,p} \leq Q_f \qquad\qquad \forall\ f \in \tilde{F}$$

9.
The injected gas at injection station i must be equal or smaller than the capacity Q_i/(Nm^3/h) of that injection station (from Table 5.6):

$$\sum_{f=1}^{F} q_{f,i} \leq Q_i \qquad\qquad \forall\ i \in \tilde{I}$$

Scenario 1 (GDC = 10 %)
In this scenario only one production unit location must be calculated: $\tilde{P}_1 = \{fp100\}$
As this scenario is quite simple, the solution can be determined easily without a computer. Therefore, this scenario also serves as a check of the approach.

Scenario 2 and 2a (GDC = 20 % and 23.3 % resp.)
For scenarios 2 and 2a the production unit set is expanded: $\tilde{P}_2 = \{fp150, wp100_{50}\}$ and $\tilde{P}_{2a} = \{fp150, wp100_{83}\}$. The other expressions remain the same.

Scenario 3 (GDC = 50 %)
The production unit set belonging to this scenario is $\tilde{P}_3 = \{fp150, wp300_{217}, wp250_{133}\}$.

Scenario 4 (GDC = 80 %)
The corresponding production unit set is
$\tilde{P}_4 = \{fp150, wp300_{217}, wp300_{179}, wp300_{144}, wp300_{110}\}$.

Scenario 5 (GDC = 100 %)
The corresponding production unit set is
$\tilde{P}_5 =$
$\{fp150, wp200_{155}, wp200_{136}, wp200_{119}, wp200_{104}, wp200_{89}, wp200_{73}, wp200_{54}, cs120\}$

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6

IS COST PRICE KILLING FOR IMPLEMENTATION OF GREEN GAS INTO THE GAS SUPPLY?

This chapter is submitted to Applied Energy (July 2014) as:
Bekkering J, Hengeveld EJ, Gemert WJTh van, Broekhuis AA. Is cost price killing for implementation of green gas into the gas supply?

Abstract
The energy efficiency and greenhouse gas reduction of a green gas supply chain, based on co-digestion, were evaluated. Therefore new definitions were introduced for energy input-output ratio, one based on primary energy as such, and one only related to energy from fossil origin. Possible improvements of green gas supply chains were investigated on the basis of these parameters, together with the influence on cost price. Results show that electricity is the major contributor to energy need when it is from fossil resources. Switching to green electricity significantly improves the energy efficiency and greenhouse

gas reduction. Preventing methane leakage during digestion and upgrading, and re-using heat within the supply chain also show improvements on these parameters and on cost price, although their influence is less. Decreasing the share of energy crops in the substrate mix shows a negative effect.

6.1 INTRODUCTION

Dutch ambitions on the future energy system are laid down in the Dutch Energy Covenant [1]. The stimulation of decentralized renewable energy production by co-operations is one of the pillars of this covenant: The Netherlands aims for 14 % renewable energy production in 2020 (currently 4 %) and 16 % in 2023. Other pillars in this covenant are saving energy as a means to improve energy efficiency, and greenhouse gas (GHG) reduction (80-95 % reduction in 2050). The goals fit in EU goals of decarbonization and increasing the share of renewable energy, and meet the vision that people's well-being, industrial competitiveness and the overall functioning of society are dependent on safe, secure, sustainable and affordable energy [2].

Biogas and green gas, in literature also referred to as biomethane, are considered to become part of the future energy system (e.g. [3],[4]), not only as an energy carrier, but also as a means to balance supply and demand of energy. At present, in The Netherlands green gas initiatives are often not profitable without subsidies ([5], [6], [7]), but it cannot be concluded plainly that green gas is too expensive. The long term perspectives of biogas will be strongly determined by possible geopolitical developments and by national and international legislation, e.g. levels of subsidies, desired energy mix, taxes and sustainability criteria [7]. It is likely that pollution by current fossil energy systems, e.g. coal-fired power plants, will be included more and more in future energy production costs. The existing EU's and Dutch energy systems need high levels of investment in the future, even in the absence of ambitious decarbonization efforts [2], which may cause uncertainty on future energy prices. Also a possible paradigm shift should be considered. In the current paradigm, gas is a commodity, available from (large) fossil reservoirs. One only pays for the amount of gas needed. Within this paradigm, supply flexibility, i.e. the ability to meet energy demand at all seasons and hours, is not a real issue. In a future paradigm with multiple renewable energy resources, balancing supply and demand will be a predominant issue, and flexibility will have to be paid for. Possibilities and costs of flexibility of green gas supply chains were investigated before ([8], [9]). Costs will be an important criterion in the future, but questions can be raised on the comparability of the current vs. future, or centralized vs. decentralized energy costs. Given the fact that green gas is considered to be part of the future energy mix, an increasing attractiveness of green gas is clearly not only determined by decreasing costs.

Thus, the question arises how a further integration of green gas into the energy system can take place. The EU and Dutch energy saving and GHG reduction goals strongly support that aiming for these goals from a plant or supply chain design engineering point of view, will stimulate the implementation of green gas in the energy supply. This is also supported by literature, e.g. [10], [11]. The energy balances of different biogas chains were studied and compared before ([12], [13], [14]), but energy optimizations within each chain were not investigated. Also the needed primary energy (PE: Refers to energy as found in nature before having undergone any conversion) within supply chains was considered to be from fossil origin, which is not necessarily the case. To the authors' knowledge, no distinction was made in scientific literature on biogas so far between primary energy from fossil or renewable resources. Considering both, i.e. without making the distinction, is an indicator of engineering energy efficiency, only considering the fossil resources is a more direct indicator related to sustainability. The distinction may be important, and can be analyzed by making modifications of a green gas supply chain and comparing these with a reference situation. Improving energy efficiency is a sound engineering objective. Replacement of fossil energy by renewable energy may reduce GHG emissions which is also a sound objective, but it not necessarily improves the energy efficiency as such. Only increasing energy efficiency of supply chains not necessarily leads to reduced energy consumption of end-users. Other policies such as taxation or regulation are required [15]. This must be considered as well, but is outside the scope of our study.

The energy balance and GHG reduction of green gas supply chains were analyzed in this study. Three sub questions were defined:

1. Based on definitions of fossil and/or renewable primary energy use, what are the contributors to energy efficiency and GHG reduction of a green gas supply chain?
2. What is the influence of selected modifications of green gas supply chains on reduction of (fossil) energy use and GHG emissions?
3. What are the consequences of these modifications to the cost price of green gas?

This study aims to add knowledge on further improving the energy efficiency and GHG reduction of green gas supply chains, in relation to costs. The used model, a reference situation, a consideration and definitions of energy efficiency and GHG reduction, and opportunities to improve these aspects are described in the following section, after which the results are presented and discussed. The study ends with conclusions and recommendations for future research.

6.2 METHOD

The considered green gas supply chain is shown schematically in Figure 6.1.

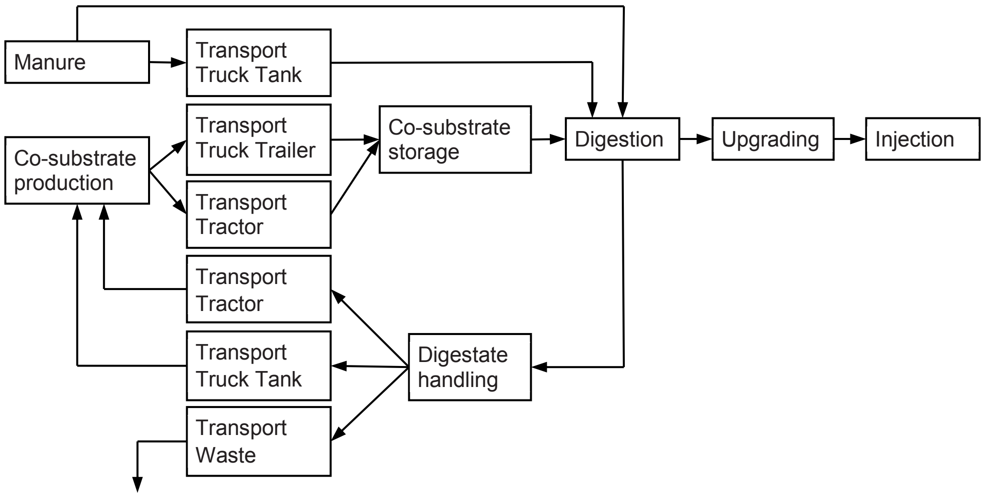

Figure 6.1: The considered reference green gas supply chain, schematically depicted, based on [16].

This supply chain model has a generic character, but in the present study a reference situation was defined, based on farm-scale co-digestion of dairy cattle manure and maize with mass fractions of 50 % each. The supply chain was modeled as consecutive transformation blocks. The biomass is digested in a single stage tank reactor and upgraded to green gas in a water wash upgrading installation. The green gas is thought to be injected into a distribution gas grid (8 bar). As a reference scale, 300 Nm^3/h was chosen for green gas injection, based on 8000 production hours a year. Part of the digestate from the digester is used on the land as a fertilizer, partly replacing artificial fertilizer according to limitations set by Dutch law, and part is considered waste. Transport comprises transport of manure and co-substrate to the farm, transport of digestate as fertilizer and transport of excess digestate as waste.

The energy inputs of each transformation block were identified, the needed energy was converted to primary energy (PE). Two distinctions were made:

1. Distinction between direct and indirect energy. Direct energy is the input energy needed for a process. For the reference situation in the present study, direct energy is in the form of diesel, natural gas or electricity. E.g. for transport of co-substrate energy is needed in the form of diesel. Indirect energy may be the energy embodied in e.g. fertilizer, machines or plants, or the energy needed for auxiliary processes (e.g. oil for tractors or trucks). All, except one, transformation blocks use direct and/or indirect energy. Manure is the exception to this, because manure is considered to be a waste stream of milk production and only has to be transported to a digester. Both direct and indirect energy are expressed in primary energy (PE).
2. Distinction between total primary energy (PE) need and primary energy need specifically from fossil resources (fossil primary energy, FPE). Except from fossil resources, PE may also be from renewables (renewable primary energy, RPE). In general, for each transformation block:

$$PE = RPE + FPE$$

   The importance of this distinction is illustrated by e.g. using the produced green gas for transport and heating (digester) within the supply chain: This does not necessarily change the PE need of each transformation block, but does change the FPE needed, because fossil resources are replaced by renewable resources. In the reference situation the needed primary energy PE is considered to be from fossil origin (FPE).

Energy efficiency is expressed as (fossil) primary energy input-output ratio. The output is the net energy available after subtracting the green gas used within the supply chain, i.e. the energy available for injection into the natural gas grid, and is depicted by the higher heating value (HHV) of one Nm^3 green gas injected: HHV = 35.63 MJ/Nm^3. Two definitions are used in this study:

1. The primary energy input-output ratio (PEIO)

$$PEIO = \frac{PE_{consumed}}{HHV}$$

   gives insight in the primary energy consumption and is defined as the ratio between the primary energy consumed ($PE_{consumed}$) at all transformation blocks in Figure 6.1 summarized for the injection of one Nm^3 green gas into the natural gas grid, and the higher heating value HHV of one Nm^3 green gas.
2. The fossil primary energy input-output ratio (FPEIO)

$$FPEIO = \frac{FPE_{consumed}}{HHV}$$

is a measure for the fossil energy consumption of all transformation blocks.

The first definition is the most direct indicator of energy consumption. FPEIO changes relatively to PEIO when renewable energy is used within the supply chain. Change of both may influence the costs. Note that our definition of FPEIO corresponds to how PEIO is usually defined in literature, e.g. [12], [17]. In the reference situation, PEIO is equal to FPEIO, as all needed energy is supposed to be from fossil origin.

The used expression for GHG reduction corresponds to prescribed calculations ([18], [19]), and uses a comparator for the fossil fuel replaced by green gas: $GHG_{comparator}$ = 0.0838 kg CO_{2eq}/MJ injected green gas [20]. The GHG reduction is then defined as:

$$GHG\ reduction = \frac{GHG_{comparator} - GHG_{chain}}{GHG_{comparator}}\ .100\ \%$$

where GHG_{chain} is the GHG emission by the supply chain per MJ injected green gas (based on HHV).

For every transformation block in Figure 6.1, used data for energy need and GHG emission calculations are shown in Table 6.1. With the conversion factors in Table 6.2 the direct energy use in Table 6.1 can be converted to fossil primary energy use.

	Energy use, direct	Energy use, indirect	GHG emissions
Manure	n.a.	n.a.	n.a.
Co-substrate production	4975 MJ_{diesel}/(ha·a)[a]	1826 MJ_{FPE}/(ha·a)[b] Seed: 240 MJ_{FPE}/(ha·a)[c] Embodied energy N: 50 MJ_{FPE}/kg[d] Embodied energy P: 8 MJ_{FPE}/kg[d] Embodied energy K: 5 MJ_{FPE}/kg[d] Embodied energy pesticides: 150 MJ_{FPE}/kg[d]	Seed: 10 kg CO_{2eq}/(ha·a)[e] Art. N fertilizer: 5.9172 kg CO_{2eq}/kg[f] Art. P2O5 fertilizer: 0.8 kg CO_{2eq}/kg[f] Art. K2O fertilizer: 0.55 kg CO_{2eq}/kg[f] Pesticides: 5.37 kg CO_{2eq}/kg[f]
Transport	1.0 MJ_{diesel}/(t·km)[g]	0.1 MJ_{PE}/(t·km)[h]	0.08764 kg CO_{2eq}/MJ_{diesel}[i]

truck tank			
Transport truck trailer	1.0 $MJ_{diesel}/(t \cdot km)$[g]	0.1 $MJ_{PE}/(t \cdot km)$[h]	0.08764 kg CO_{2eq}/MJ_{diesel}[i]
Transport tractor	1.7 $MJ_{diesel}/(t \cdot km)$[h]	0.8 $MJ_{PE}/(t \cdot km)$[h]	0.08764 kg CO_{2eq}/MJ_{diesel}[i]
Co-substrate storage	-	Embodied energy concrete: 2 MJ_{FPE}/kg[j]	-
Digestion	0.4 kWh/Nm^3 biogas (heating, natural gas)[k] 0.12 kWh/Nm^3 biogas (electricity)[k]	Embodied energy concrete: 2 MJ_{FPE}/kg[j] Embodied energy steel: 24 MJ_{FPE}/kg[j]	0.0838 kg CO_{2eq}/ $MJ_{nat.\ gas}$[l] 0.198 kg CO_{2eq}/ MJ_{el}[m]
Upgrading	0.24 kWh/Nm^3 biogas (electricity)[n]	Embodied energy steel: 24 MJ_{FPE}/kg[j]	0.198 kg CO_{2eq}/ MJ_{el}[m]
Injection	0.01 kWh/Nm^3 green gas (electricity)	Embodied energy steel: 24 MJ_{FPE}/kg[j]	0.198 kg CO_{2eq}/ MJ_{el}[m]

Table 6.1: Used data in the reference situation.
[a] derived from [14], [18], [21].
[b] [21].
[c] [14].
[d] derived from[14], [17], [21], [22].
[e] [23].
[f] derived from [22], [23], [24], [25].
[g] derived from [14], [17], [22], [26], [27], [28].
[h] [17].
[i] derived from [22], [28], [29], [30].
[j] derived from [17], [31].
[k] derived from [5], [12], [14], [32].
[l] derived from [20], [22], [33].
[m] derived from [22], [33], [34].
[n] derived from [5], [14], [22].

	Fossil primary energy use
Diesel	1.25 MJ_{FPE}/MJ_{diesel}[a]
Natural gas	1.1281 $MJ_{FPE}/MJ_{nat.gas}$[b]
Electricity	2.5 MJ_{FPE}/MJ_{el}[c]

Table 6.2: Conversion factors. Note that the primary energy use and hence GHG emissions of electricity from fossil resources are significantly more than of diesel and natural gas.
[a] derived from [12], [14], [17], [21], [22], [35].
[b] [22].
[c] derived from [12], [14].

Indirect energy was considered not to be affected and hence not optimized, and is therefore expressed in FPE.

Based on literature review and interviews, eight opportunities were identified for optimization of the supply chain, based on the Trias Energetica: saving energy, using renewable energy, clean use of fossil energy [36]. These opportunities were modeled as modifications of the reference situation. Where applicable, for each opportunity the reference situation is described first.

Digester leakage:
Minimizing methane losses at digestion. Values for digester losses as found in literature are presented in Table 6.3.

Methane losses/%	Quantification method	Reference
1	assumption	[33]
1	assumption	[37]
2	assumption	[23]
3	assumption	[38]
0.17-5.46	measurement	[39]
3	measurement	[40]

Table 6.3: Methane losses during digestion.

In the reference situation 1 % of the methane production of the digester is considered to be lost. Note that measured values are often higher. Lack of maintenance shows to be an important cause for high leakages. The digester methane loss is changed to 0.1 % which results in a higher biogas yield. The value is based on proper design and maintenance of biogas plants. It is assumed that this is possible without extra investment costs.

Upgrading leakage:
Minimizing methane losses at upgrading. From the technologies that are currently on the market, water scrubbing is among the technologies with the greatest GHG emission savings [41]. The methane efficiency was changed from 99 % in the reference situation to 99.9 %. This is based on available post-treatment technologies which can be implemented to deal with methane slip. These include regenerative thermal oxidation, recuperative thermal oxidation and biological de-methanization. It is assumed that this is possible without extra investment costs.

Re-use heat:
Re-use heat within the supply chain. A pinch analysis ([11], [42]) was performed to explore the possibilities. This showed that 1.2 MJ/Nm^3 can possibly be saved by re-using the digestate heat and the compression heat at upgrading for heating the biomass. This opportunity implies that digestion and upgrading installations are closely interconnected. Improved insulation of digesters is not investigated separately: The impact would be modest, because heat demand is mainly determined by increasing the biomass temperature to mesophilic conditions. An extra investment of 100 k€ is assumed.

Digestate fertilizer:
Increase of artificial fertilizer replacement by digestate. The rationale of this opportunity is that in the reference situation the largest share of digestate is considered as waste, which has to be paid for, while energy cost and environmental impact of artificial fertilizer is considerably (e.g. [11]). However, the uptake of nutrients in digestate by crops is limited compared to artificial fertilizer. Therefore only a modest 10 % increase of digestate use is considered. Savings are mainly caused by less needing artificial fertilizer and partly by not needing to transport digestate as waste (50 km in the model). Transport to arable land increases in this case.

Manure 75 %:
A change to less maize in the mixture. Co-digestion of cattle manure and maize with mass fractions 75 % and 25 % respectively is chosen.

Mono-digestion manure:
Mono-digestion of cattle manure. Mono-digestion is still in development, but is stimulated in the Netherlands by subsidies [5].

Green fuel:
Using green gas for transport within the supply chain and heating the digester. In the reference situation, 12.4 % of the energy consumption is used for transport, and natural gas is assumed to be used for heating of the digester. Extra investment costs for adapting tractors and trucks, and compression of the gas to 200 bar, are included and assumed to be 200 k€. The energy (work) needed for compression from 8 to 200 bar is estimated to be 0.45 kWh/Nm^3. The PEIO calculated for the reference situation is also applied to green gas use as a transport fuel.

Green electricity:
Electricity is from renewable resources. Electricity is used at digestion, upgrading and injection. If this is from renewable resources, then fossil energy (FPE) use and GHG emissions are strongly reduced. The factor 2.5 for (F)PE calculation (Table 6.2) is changed to 1.1 [43]. We assumed no influence on the cost price of electricity.

Changing the green gas quality from 89 % to e.g. 98 % was not considered [44]. Although the transport of green gas would become more efficient, i.e. more energy per Nm^3 transported, it would not influence the supply chain as it was defined. Methane enrichment of biogas by methanization of hydrogen and carbon dioxide might be an interesting option as well (e.g. [45]), but was also not considered. As this technology is still in development, (investment) costs in relation to methane yield are not available.

The opportunities, implemented as modifications of the reference situation, were analyzed in terms of influence on (F)PEIO, GHG reduction and cost price, and compared to the reference situation.

6.3 RESULTS/DISCUSSION

As stated before, in the reference situation PEIO is equal to FPEIO. This is shown in Figure 6.2a as a function of scale. The value at the reference scale 300 Nm^3/h is 32.8 %.

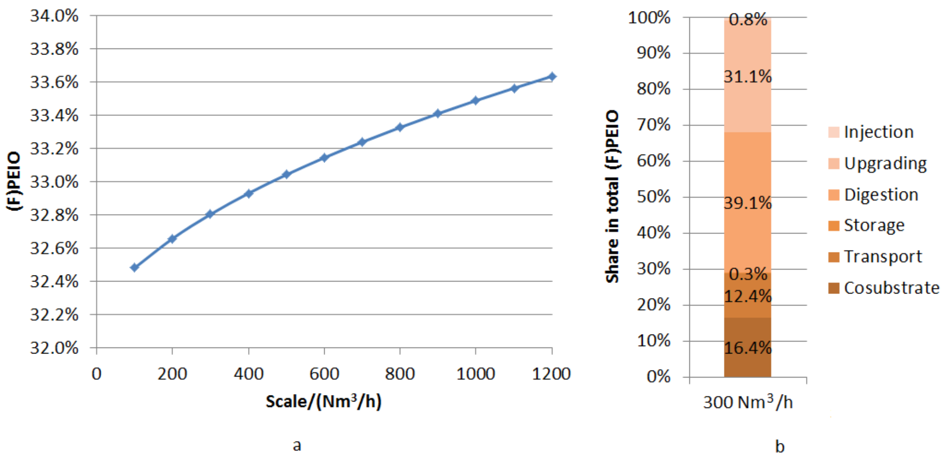

Figure 6.2: a) (F)PEIO as a function of scale. The abscissa is the quantity of green gas in Nm^3/h injected into a distribution gas grid, based on 8000 production hours a year. b) Share of consecutive transformation blocks in total PE use at scale 300 Nm^3/h.

The increasing PE consumption at increasing scale is caused by increasing transport distances. The share of the consecutive transformation blocks in Figure 6.1 in total PE consumption is depicted in Figure 6.2b for scale 300 Nm^3/h, where the transport transformation blocks are combined. As can be seen in the Figure, the largest PE consumption is caused by digestion and upgrading. For scale 300 Nm^3/h, a subdivision in direct and indirect energy is shown in Figure 6.3. The share of indirect PE in the total PE consumption is 8.8 %.

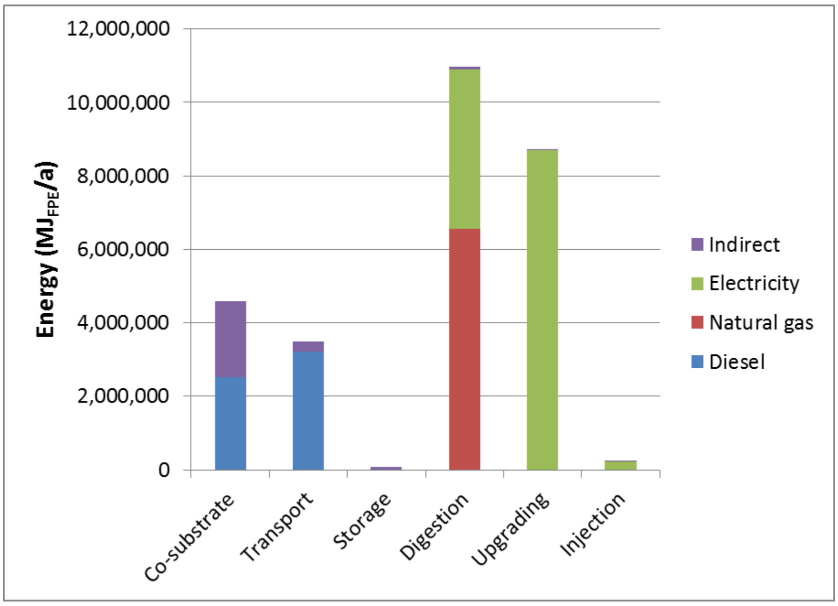

Figure 6.3: Subdivision in direct and indirect energy use of the process steps (scale 300 Nm^3/h). The total primary energy consumption is 28.0×10^6 MJ/a. At this scale, the annual energy production is 85.5×10^6 MJ/a (PEIO = 32.8 %).

The large FPE use of digestion and upgrading is caused by a large heating demand (digestion) and electricity use (digestion and especially upgrading) with a relatively large conversion factor of electricity to primary energy (Table 2).

The GHG reduction as a function of scale is shown in Figure 6.4a. The decreasing GHG reduction at increasing scale is caused by increasing transport distances for manure, co-substrate and digestate.

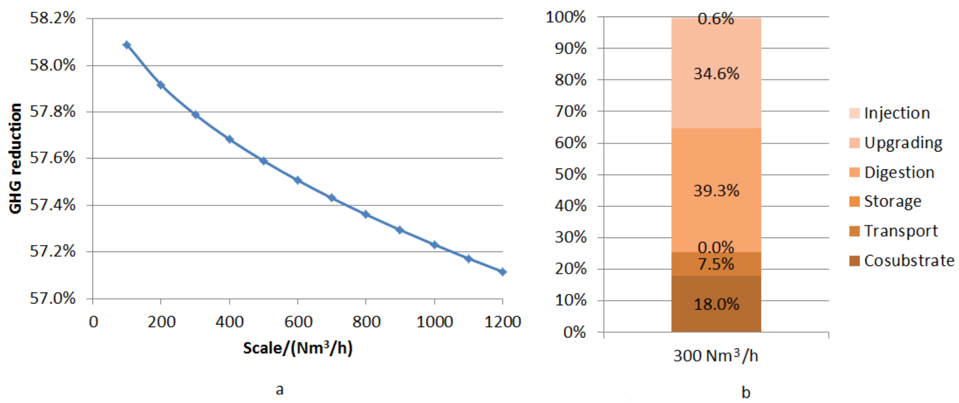

Figure 6.4: a) GHG reduction as a function of scale. The abscissa is the quantity of green gas in Nm^3/h injected into a distribution gas grid, based on 8000 production hours a year. b) Share of consecutive transformation blocks in GHG reduction at scale 300 Nm^3/h.

The share of the consecutive transformation blocks in Figure 6.1 in total GHG reduction is depicted in Figure 4b for scale 300 Nm^3/h. At this scale the GHG reduction is 57.8 %. For the co-substrate these are caused by direct (fossil fuel use) and indirect (machines, seeds, fertilizer, pesticides) energy use, for transport mainly by fossil fuel use. GHG emissions of digestion are caused by methane emissions (48 % of digestion total, the global warming potential of methane is 23 times worse than CO_2), electricity use (39 %) and heat use (13 %). The upgrading share is caused by methane losses (34 %) and electricity use (66 %). Finally, the emissions at injection are mainly caused by electricity use. The largest shares are caused by methane leakage/slip during digestion and upgrading. Because of this effect, the share of transport in GHG emissions is relatively lower than its FPE share in Figure 6.2b. CO_2 emissions from the upgrading process are not considered because release of CO_2 is part of the short cycle. CO_2 capture by growing maize is also not taken into account. In the used model GHG emissions of manure are not taken into consideration, because manure is considered a waste stream of milk production. From this point of view, GHG emissions from manure should be accounted for in the process of milk production.

Summarizing, for the reference situation (scale 300 Nm^3/h), (F)PEIO is 32.8 %, the GHG reduction is 57.8 %, and the cost price was calculated to be 72.0 €ct/Nm^3.

The implications of the considered opportunities are shown in Table 6.4. A combination of opportunities which have a score '+' or 'o' on all aspects, i.e. no '-', was added to explore the limits in improvements.

	PEIO/%		FPEIO/%		GHG reduction/%		Cost price/(€ct/Nm^3)	
Reference	32.8	o	32.8	o	57.8	o	72.0	o
Digester leakage	32.7	+	32.7	+	62.4	+	71.6	+
Upgrading leakage	32.3	+	32.3	+	62.8	+	71.0	+
Re-use heat	29.0	+	29.0	+	61.2	+	71.5	+
Digestate fertilizer	32.5	+	32.5	+	58.2	+	71.9	+
Manure 75 %	36.3	-	36.3	-	55.8	-	(66.0)	+
Mono-digestion	54.7	-	54.7	-	44.5	-	(49.2)	+
Green fuel	35.3	-	19.1	+	69.6	+	81.7	-
Green electricity	24.1	+	17.9	+	71.5	+	72.0	o
Combination	19.7	+	13.6	+	84.5	+	70.4	+

Table 6.4: Effects of opportunities on (F)PEIO, GHG reduction and cost price. A plus (+) depicts an improvement compared to the reference situation, i.e. a lower value for (F)PEIO or cost price, and a higher value for GHG reduction. A minus (–) is an impairment, and a 'o' depicts no change. NB1: For all cases the injection capacity remains 300 Nm^3/h. NB2: Although not shown quantitatively, lower losses at digestion and upgrading positively influence the amount of needed resources, i.e. less resources are needed.

The first four opportunities (digester and upgrading leakage, re-using heat and increase of digestate as fertilizer) improve the performance of green gas supply chains, although the influence is modest. These are the only opportunities which show improvements on all considered aspects.

Opportunities Manure 75 % and Mono-digestion should be considered with some caution. In the used model, the digestion costs are based on investment costs as a function of produced quantity of biogas. However, in these two cases the share of manure strongly increases. As the energy content of manure is much less than maize, much substrate would be needed for the same green gas production. I.e., the digester would be much larger and more expensive than assumed in the model. So in practice the costs will be higher than presented. Therefore these are shown between brackets. The strongly increased (F)PEIO and decreased GHG reduction are caused by increased transport movements because of the increased needed quantity of manure. If avoided emissions from manure would be taken into account, the results would be different. Avoiding these emissions is one of the reasons to digest manure.

The difference between PEIO and FPEIO becomes clear at opportunities Green fuels and Green electricity. Both clearly give a reduction in fossil energy use, and thus GHG emissions. The higher cost price of opportunity 'Green fuel' is mainly caused by the relatively high costs of compression of gas to 200 bar. The high electricity need for this, which is still considered to be from fossil origin, is not advantageous. The net reduction in FPEIO is caused by using green gas as a fuel in the supply chain. Of all opportunities, from a sustainability point of view, green electricity gives the largest improvement of the supply chain.

6.4 CONCLUSIONS – FUTURE RESEARCH

In the present study an alternative way to present the energy efficiency of green gas supply chains was introduced. A distinction was made between direct and indirect energy. The share of indirect energy in total energy consumption is modest. A further distinction was made between primary energy (PE) as such, and the primary energy from fossil origin (FPE). The first is a direct indicator for energy efficiency, the latter is an indicator of energy use from a sustainability perspective. The influence of several opportunities to improve the sustainability of green gas supply chains was investigated.

An obvious result is that preventing methane losses and re-using heat should always be strived for (opportunities Digester leakage and Upgrading leakage), although on these aspects to date no legislation is known to the authors. Increase of digestate as fertilizer seems promising, but more research is required on aspects like nutrient uptake by plants and soil improvement by digestate. Using compressed green gas for transport within the supply chain would seem obvious, but the costs of compression are very high. Moreover, for this opportunity the FPEIO is still some 26.9 %. Using green gas for heating the digester is more obvious, but was not investigated separately. The effect of using sustainable electricity is evident, a subsidy regime requiring the use of sustainable electricity would significantly contribute to achieving national sustainability goals. At the current state of technology, only the combination of opportunities with a positive score would help to reach long-term goals of more than 80 % GHG reduction. In that case the fossil energy use could be significantly reduced. The cost price decrease is modest, but possibilities to make green gas supply chains more viable seem to be there. In the present study only maize was considered as co-substrate. The influence of other co-substrates on cost price and sustainability should be investigated.

In this study only the injection of green gas was considered. How the results relate to other applications of biogas or green gas might be subject of future research. Comparison of natural gas replacement with compressed green gas for transport may give other results. Separation of nutrients in the digestate might also open interesting opportunities for further optimizing green gas supply chains. At least the nitrogen use as a fertilizer might further increase to some 250 kg/ha instead of 190 kg/ha which was used in the study. A further investigation of embodied energy of plants and machines was not subject of this study. Improvements in the mechanical design of plants and machines, or in the production of artificial fertilizer might open interesting pathways for further 'greening' of green gas supply chains. It does not contribute to fossil energy replacement to a great extent, but to sustainable use of resources in general.

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SUMMARY

In order to gain a more mature share in the future energy supply, green gas supply chains face some interesting challenges. In this thesis green gas supply chains, based on co-digestion of cow manure and maize, are considered. The produced biogas is upgraded to natural gas quality and injected into the existing distribution gas grid and thus replacing natural gas. Literature research showed that relatively much attention has been paid up to now to elements of such supply chains. Research into digestion technology, agricultural aspects of (energy) crops and logistics of biomass are examples of this. This knowledge is indispensable, but how this knowledge should be combined to help understand how future green gas systems may look like, remains a white spot in the current knowledge. This thesis is an effort to fill this gap. A practical but sound way of modeling green gas supply chains was developed, taking costs and sustainability criteria into account. The way such supply chains can deal with season dependent gas demand was also investigated. This research was further expanded into a geographical model to simulate several degrees of natural gas replacement by green gas. Finally, ways to optimize green gas supply chains in terms of energy efficiency and greenhouse gas reduction were explored.

A model, including indicators for sustainability, was proposed to calculate the cost price of green gas as a function of scale. The cost price calculation corresponds to the existing Dutch renewable energy subsidy regime, based on a net present value calculation of 12-year projects. It was confirmed that cost price decreases at increasing scale. Sustainability of supply chains is quite difficult to grasp. Literature shows a variation in approaches and detail, ranging from only considering land use or energy efficiency to defining a set of sustainability indicators which were quantified as much as possible. It is difficult to objectively quantify such indicators. Recognizing that sustainability comprises people, planet and profit, we chose to implement some practical matters in the model, e.g., energy analysis and number of transport movements were implemented, but not a full life cycle analysis was carried out. At the scales considered (farm-scale), global aspects of sustainability are not relevant. Global aspects are biomass production abroad and international transport, with social (e.g., working circumstances) and environmental (e.g., cutting rain forests for energy purposes) consequences. Energy use of the supply chain is clearly dominated by digestion and upgrading. The number of transport movements may be a limiting factor for upscaling biogas production. The extent to which this is possible, is primarily a societal consideration, but some 250 Nm^3/h green gas production seems to be a practical upper scale limit. It was assumed that 25 % of the agricultural land could be

used for green gas production purposes. Even with this optimistic assumption, it would be hard to achieve the envisioned green gas production of 1500 million Nm^3 per year.

One of the issues concerning the replacement of natural gas by green gas is the seasonal pattern of the gas demand. When constant production is assumed, this may limit the injected quantity of green gas into a gas grid to the level of the minimum gas demand in summer. To be able to analyze the possibilities of balancing gas supply and demand with a green gas supply chain, the model described above was adapted. The applicability of modeling yearly gas demand data in a geographical region by Fourier analysis was investigated. The seasonal swing factor was introduced, which is the maximum of the sine function divided by the minimum. Values of this seasonal swing factor may range from about 20 (households) to 1.2 (specific companies with a rather constant gas demand). For a sine shape gas demand, three scenarios were further investigated: varying biogas production in time, adding gas storage to a supply chain, and adding a second digester to the supply chain which is assumed to be switched off during the summer months. A regional gas demand modeled by a sine function is reasonable for household type of users as well as for business areas, or a mixture of those. Of the considered scenarios, gas storage is by far the most expensive. To meet gas demand by a green gas supply chain, flexible biogas production showed to be the most promising from a cost price point of view. However, this is not the way digesters are built and operated nowadays. Further research in this direction might open interesting pathways to sustainable gas supply chains.

The results described above were used in a study to investigate an increase in gas demand coverage by green gas in a geographical region, i.e., the extent to which natural gas demand can be replaced by green gas. A procedure was proposed which comprises two steps. In the first step, the types and number of green gas production units (biogas production and upgrading) are determined, based on a desired gas demand coverage. The production types comprise time-varying biogas production, non-continuous biogas production (only in winter periods with each unit having a specified production time) and constant production including seasonal gas storage. The sequence of application of these production types is important because it is based on increasing costs. In the second step locations of production units and injection stations are calculated using mixed integer linear programming, with cost price minimization being the objective. Five scenarios were defined with increasing gas demand coverage, representing a possible future development in natural gas replacement. The scenarios comprise 10, 20, 50, 80 and 100 % gas demand coverage. The results show that production locations differ for each scenario, but are connected to a selection of injection stations, at least in the considered geographical region under the assumed preconditions. The cost price is mainly determined by the type of digesters needed. Increasing gas demand coverage does not necessarily mean a much higher cost price.

Compared to the current natural gas price, the above studies showed that costs of green gas are high in all cases. However, not only costs determine the feasibility of green gas. Energy saving and greenhouse gas reduction are important targets set by the EU and the (Dutch) government. Therefore, the energy efficiency and greenhouse gas reduction of a green gas supply chain, based on co-digestion, were further investigated. A new distinction between definitions of energy input-output ratio was introduced, one based on primary energy as such, and one only related to energy from fossil origin. Possible improvements of green gas supply chains were investigated on the basis of these parameters, together with the influence on cost price. Results show that switching from fossil to green electricity significantly improves the (fossil) energy efficiency and greenhouse gas reduction. Preventing methane leakage during digestion and upgrading, and re-using heat within the supply chain also show improvements on these parameters and on cost price, although their influence is less. Decreasing the share of energy crops in the substrate mix shows a negative effect. It was shown that with the current technology greenhouse gas reductions of more than 80 % are possible. Multiple improvement options will necessarily have to be implemented in green gas supply chains, in order to meet the sustainability targets set by the EU.

Overall it can be concluded that the used modeling approach gives opportunities to investigate variations in green gas supply chains in a practical way. By combining elements of such supply chains costs were investigated, in relation to scale, in relation to season dependent gas demand, and in relation to the degree of natural gas replacement. Future research may comprise e.g. flexible biogas production and a useful application of digestate. An extension of this research may be the further exploration of possible biogas production locations, together with governments, farmers and other stakeholders. Optimal use of arable land or waste streams are part of this.

SAMENVATTING

Om een meer volwaardig aandeel te krijgen in de energievoorziening van de toekomst, zijn er voor groengasketens nog een paar interessante uitdagingen. In deze dissertatie worden groengasketens beschouwd die zijn gebaseerd op covergisting van koeienmest en maïs. Het geproduceerde biogas wordt opgewaardeerd tot aardgaskwaliteit en geïnjecteerd in het bestaande gasdistributienet, en vervangt daarmee aardgas. Literatuuronderzoek heeft laten zien dat tot op heden relatief veel aandacht is besteed aan onderdelen van zo'n keten. Onderzoek naar vergistingstechnologie, landbouwkundige aspecten van (energie)gewassen en de logistiek van biomassa zijn hier voorbeelden van. Deze kennis is onmisbaar, maar hoe deze kennis gecombineerd moet worden om beter te begrijpen hoe toekomstige groengasketens eruit zouden kunnen zien, is nog een witte vlek in de huidige kennis. Deze dissertatie is een poging om dit gat te dichten. Een praktische manier om groengasketens te modelleren is ontwikkeld, rekening houdend met kosten en duurzaamheidscriteria. Hoe zulke ketens om kunnen gaan met een seizoensafhankelijke gasvraag is ook onderzocht. Dit onderzoek is verder uitgebreid naar een geografisch model om verschillende niveaus van aardgasvervanging door groen gas te kunnen onderzoeken. Tot slot zijn optimalisaties van groengasketens onderzocht in termen van energie-efficiëntie en CO_2-reductie.

Een model is ontwikkeld om de kostprijs van groen gas als functie van de schaalgrootte te kunnen berekenen. In dit model zijn indicatoren voor duurzaamheid opgenomen. De kostprijsberekening komt overeen met het bestaande Nederlandse subsidiestelsel, gebaseerd op een netto contante waardeberekening over 12 jaar. Dat de kostprijs daalt bij toenemende schaalgrootte werd bevestigd. Duurzaamheid is lastig om grip op te krijgen. De literatuur laat een veelheid aan benaderingen en detail zien, variërend van het beschouwen van alleen landgebruik of energie-efficiëntie, tot een set aan duurzaamheidsindicatoren die zo goed mogelijk worden gekwantificeerd. Het is moeilijk om dit objectief te doen. Rekening houdend met het gegeven dat duurzaamheid zowel 'people', 'planet' als 'profit' betreft, hebben we ervoor gekozen om enige praktische aspecten in het model op te nemen. Een energieanalyse en het aantal transportbewegingen werden bijvoorbeeld wel in het model meegenomen, maar een volledige levenscyclusanalyse werd niet uitgevoerd. Bij de beschouwde schaalgroottes ('boerderijschaal') zijn duurzaamheidsaspecten op wereldniveau niet relevant. Daarbij gaat het om biomassaproductie in het buitenland en internationaal transport, met sociale (arbeidsomstandigheden) en milieukundige (bijvoorbeeld het kappen van regenwouden voor energiedoeleinden) consequenties. Het energiegebruik van de groengasketen wordt gedomineerd door vergisting en upgrading. Het aantal transportbewegingen kan een beperkende factor zijn voor het opschalen van biogasproductie. De mate waarin dit mogelijk is, is vooral een maatschappelijke afweging, maar ongeveer 250 Nm^3/h lijkt een praktische bovengrens te zijn. Aangenomen werd dat 25 % van de landbouwgrond kan worden gebruikt voor groengasdoeleinden. Zelfs met deze optimistische aanname is het moeilijk tegemoet te komen aan het streven naar 1500 miljoen Nm^3 groen gas per jaar.

Een van de vraagstukken met betrekking tot aardgasvervanging door groen gas is de seizoensafhankelijkheid van de gasvraag. Wanneer een constante gasproductie wordt aangenomen, kan dit de geïnjecteerde hoeveelheid groen gas in het gasnet beperken tot de minimale gasvraag in de zomerperiode. Om de mogelijkheden van het balanceren van gasvraag en –aanbod met een groengasketen te kunnen analyseren, werd het hierboven beschreven model aangepast. De toepasbaarheid van Fourieranalyse om de jaarlijkse gasvraag te modelleren, is onderzocht. Hierbij werd de 'seasonal swing factor' geïntroduceerd, dat is het maximum van de sinuscurve gedeeld door het minimum. De waarde van de seasonal swing factor kan variëren tussen ongeveer 20 (voor huishoudens) en 1.2 (bepaalde bedrijven met een bijna constante gasvraag). Voor een sinusvormige gasvraag zijn drie scenario's onderzocht: tijdsafhankelijke biogasproductie, gasopslag toevoegen aan de keten, en het toevoegen van een tweede vergister aan de keten die gedurende de zomermaanden afgeschakeld kan worden. Een regionale gasvraag, gemodelleerd met een sinusfunctie, is zowel voor huishoudens als voor bedrijventerreinen, of een combinatie daarvan, een redelijke weergave. Van de beschouwde scenario's is gasopslag veruit het duurst. Om aan de gasvraag te voldoen met een groengasketen is flexibele productie vanuit kostenoogpunt het meest belovend. Echter, tot op heden worden vergisters niet voor dit doel gebouwd en bedreven. Verder onderzoek op dit punt zou interessant kunnen zijn.

De hiervoor beschreven resultaten zijn gebruikt in een studie om een toename in aardgasvervanging door groen gas in een geografische regio te onderzoeken. Een procedure is ontwikkeld die uit twee stappen bestaat. In de eerste stap worden het type en aantal groengasproductie-units bepaald, gebaseerd op de gewenste mate van aardgasvervanging. De productietypes omvatten flexibele biogasproductie, niet-continue biogasproductie (alleen in de winterperiode waarbij elke unit een specifieke productietijd heeft) en constante productie met seizoensopslag. De volgorde van deze drie opties is daarbij belangrijk vanuit kostenoogpunt. In de tweede stap worden productielocaties en locaties voor injectiestations berekend met behulp van mixed integer lineair programmeren. Kostprijsminimalisatie is daarbij het doel. Vijf scenario's zijn gedefinieerd met toenemende aardgasvervanging; dit zou een mogelijke ontwikkeling in aardgasvervanging weer kunnen geven. Deze scenario's zijn resp. 10, 20, 50, 80 en 100 % aardgasvervanging. De resultaten laten voor de beschouwde regio en de gekozen randvoorwaarden zien dat de productielocaties voor elk scenario verschillen, maar dat ze verbonden zijn aan een beperkt aantal injectiestations. De kostprijs wordt vooral bepaald door het type productie-unit dat benodigd is. Een toenemende aardgasvervanging betekent niet automatisch een toenemende kostprijs.

Vergeleken met de huidige aardgasprijzen laten de hierboven beschreven studies zien dat de kosten van groen gas hoog zijn. Echter, de toepasbaarheid van groen gas wordt niet alleen door de kosten bepaald. Energiebesparing en CO_2-reductie zijn belangrijke doelen voor zowel de EU als de (Nederlandse) regering. Daarom zijn de energie-efficiëntie en CO_2-reductie van een groengasketen op basis van covergisting verder onderzocht. Een nieuw onderscheid tussen definities van energie input-outputratio is geïntroduceerd, de ene gebaseerd op primaire energie in totaliteit, de andere specifiek gerelateerd aan fossiele primaire energie. Op basis van deze parameters zijn mogelijke optimalisaties van groengasketens onderzocht, met daarbij de invloed op de kostprijs. De resultaten laten zien dat overgaan van fossiele naar groene elektriciteit de (fossiele) energie-efficiëntie en CO_2-reductie significant verbetert. Het voorkomen van methaanverlies bij vergisting en upgrading, en hergebruik van warmte binnen de keten laten ook verbeteringen zien op de gekozen parameters en de kostprijs, hoewel hun invloed wel minder is. Het verminderen van het aandeel van energiegewassen in de substraatmix heeft een negatief effect. Met de huidige technologie is een CO_2-reductie van meer dan 80 % mogelijk. Meerdere verbeteringsopties zijn nodig voor groengasketens om aan de duurzaamheidsdoelstellingen van de EU te voldoen.

In zijn algemeenheid kan worden geconcludeerd dat de toegepaste modellering mogelijkheden biedt om variaties in groengasketens op een praktische manier te onderzoeken. Door de elementen van dergelijke ketens te combineren zijn de kosten onderzocht, als functie van schaalgrootte, in relatie tot seizoensafhankelijke gasvraag, en in relatie tot een gewenst niveau van aardgasvervanging. Het zou goed zijn om flexibele biogasproductie en nuttige toepassing van digestaat verder te onderzoeken. Het onderzoek kan worden uitgebouwd door verder naar mogelijke biogasproductielocaties te kijken, samen met overheden, boeren en andere belanghebbenden. Optimaal gebruik van landbouwgrond of afvalstromen maken hier deel van uit.

BIOGRAPHY

Jan Bekkering was born on 12 February 1971 in Gieten, The Netherlands. He attended secondary school at the Ubbo Emmius Lyceum in Stadskanaal from 1983 to 1989. He studied Mechanical Engineering at the University of Twente from 1989 to 1995, and graduated with a specialization in Biomedical Engineering.

After his studies he had a career in two companies, the first company being a manufacturer of trailer wheels and other steel products, the second a manufacturer of mobile hydraulic lifting equipment. Development and engineering of new products, prototype testing and project management characterized his tasks.

Since 2003 he is a lecturer at the department of Mechanical Engineering at Hanze University of Applied Sciences in Groningen. Besides lecturing on mechanics and (methodical) design, supervising graduates belongs to his responsibilities. In 2007 he started his part-time PhD research at the Center of Applied Research and Innovation – Energy. This gave him the opportunity to broaden and deepen his knowledge, and to connect actual research results to education. He has a strong interest in renewable energy and sustainable design of products and systems. On these topics he developed courses on a bachelor's and master's level.

His societal interest and involvement is manifest in being a council member of the municipality of Hoogeveen since 2010.